Introduction to semiconductor physics in secondary education: evaluation of a teaching sequence

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Abstract. This article presents a didactic proposal oriented to teaching notions of semiconductor physics in Secondary Education [SE]. The methods and the results of a pilot study designed to analyze the effectiveness of a teaching sequence on the topic are also described. The subjects were 60 students, aged 14–15 years, of a secondary school in Seville [Spain]. The levels of knowledge acquired by the students were evaluated by means of a test and personal interviews, which we also used to detect the most frequent obstacles they encountered against learning. Also, we employed personal interviews and analysis of the students' notebooks to evaluate (a) their attitudes towards semiconductor physics and its learning, and (b) the degree to which the teaching sequence fosters cooperative learning and the self-regulation of learning. The results indicated that the students in general acquired (1) ideas and reasoning in the appropriate line, although with some mistakes or inaccuracies with respect to scientific conceptions, and (2) positive attitudes towards the learning of semiconductor physics, with a high degree of motivation during the teaching-learning process. The conclusion is that it is possible to initiate teaching the basic notions of semiconductor physics in SE, although it is necessary to continue going deeper into the topic with new research. As a proposal for improvement in future actions, we formulate new objectives oriented at overcoming the students' commonest obstacles against learning with respect to the topic.

Keywords: evaluation; physics education; secondary school; semiconductor physics; teaching sequence.

Introduction

The field of electronics and electronic products is of outstanding relevance to today's world. It has a significant presence in the workplace, at home, and in educational, cultural, and leisure environments (Butterfield, 2004). As a consequence, it has become necessary for young people to acquire a basic and adequate education in this scientific and technological discipline from an early age (Barak, 2002).

Spain's educational system introduces content of electronics beginning with the 2nd Cycle of Secondary Education [SE] [14-16 years of age] as part of the technology curriculum. Students learn the functioning and basic applications of the most elementary electronic components [diodes, transistors, condensers…] through a 'systems approach' (Geddes, 1984), i.e., by studying their function in a system or electronic circuit. The physical aspects governing the behaviour of the systems are usually not dealt with.

The advances in solid state physics —in particular semiconducting solids— have been the underlying reason for the outstanding developments in the science of electronics (Jenkins, 2005). We therefore believe that it may be interesting to include the study of elementary notions of semiconductor physics in SE, as part of the education in electronics currently being developed for this stage of education.

Electronics has for years been included in both the SE technology and SE science [physics and chemistry] curricula in countries such as France (e.g. Polev, 1989), the United Kingdom (e.g. Ainley, 1984; Bevis, Gough & Deeson, 1985; Murphy et al., 2004; Summers, 1985), Albania (Corati, Mulaj & Corati, 1995), Israel (Barak, 2002), and Finland (Lavonen & Meisalo, 2000, 2003). Finland, for example, is developing an educational project denominated GEP [Get Electronics Project], whose aim is the coordinated introduction of electronics into the SE science and technology curriculum.

But, in spite of the emerging awareness of the need to integrate electronics content into the science curriculum, we find that semiconductor physics has not yet received attention in that process. The treatment given to electronics in the science curriculum of the aforementioned countries is usually functional, copying the approach in the area of technology, i.e., without going into the physical foundations. Indeed, in the literature we have found no research that refers to the teaching and learning of semiconductor physics.

We are not suggesting that teaching semiconductor physics should be obligatory in SE. We think that it must be the result of the perception on the part of each particular science teacher of a need to present some of this material at this educational stage. And also that, for this purpose, the teacher must bear in mind the real possibilities that correspond to the ages of the students and the current science curriculum. In our case, this perception was a result of the first of the authors teaching both science and technology to his SE students. After some years teaching electronics to the students in the area of technology, he felt that there was a need to complement this teaching by introducing some notions of semiconductor physics in his science classes (García-Carmona, 2006).

Taking into account the present SE science curriculum, and with an appropriate educational and methodological approach, we think that it is possible to integrate some of these basic notions on the topic into the science class.

To put the project into practice, we prepared a teaching sequence establishing as the departure point the content relative to matter and electricity. Students at this level already have to handle explanations of such physical properties as the insulating/conducting behaviour of a material based on (1) the type of chemical bond [covalent/metallic], and (2) the mobility of valence electrons [localized electrons forming the covalent bonds *vs.* electrons free to move throughout the conductor]. To teach semiconductor physics, we add to these ideas a few more that SE students can understand on the basis of a simple model [a plane model of the atomic covalent bond], and with the aid of some easily analyzed analogies taken from their prior knowledge and experience. In particular, amongst other things, we are referring to:

- The possibility of representing the promotion of bound electrons [in solids of certain elements of the periodic table] so that they can move throughout the material, by means of thermal agitation that is sufficiently strong to break some bonds and release those electrons.
- The idea of the 'hole' left by the electron released from a broken bond, whose apparent motion through the semiconductor —opposite to that of the free electron— allows it to be regarded as a positive charge carrier.

In this article, we first describe the general characteristics of the teaching programme. Then, we present the results and conclusions of a pilot study targeted at analyzing the effectiveness of the designed teaching sequence. The analysis evaluates: (a) the levels of knowledge reached by the students in terms of the anticipated learning objectives; (b) the most frequent learning obstacles; (c) the way in which the methodological approach used in the teaching fosters the students' learning; and (d) the attitudes acquired by the students towards semiconductor physics and its learning. Finally, in light of the results, we present a proposal for improvement based on reformulating the learning objectives to overcome the learning obstacles observed in successive implementations of the teaching sequence.

The teaching programme

Considering the current SE science curriculum in Spain, we based the design of our teaching sequence on the following educational criteria:

- *A priori* the students 'will activate inappropriate conceptions on semiconductor physics' because they have not studied the topic previously. This means that the starting point must be their prior knowledge about similar topics, in this case, matter and electricity.
- The *transposition didactique* of semiconductor physics for the SE level must be done in such a way that the concepts of the topic connect appropriately with the content on matter and electricity established in the current science curriculum for this level. Therefore, those concepts of semiconductor physics which can not be constructed directly from the content of the said curriculum will be excluded from the learning goals. Also, the models and semeiotic registers that are introduced must be in syntony with SE students' cognitive capacities, which usually are suggested in the official curriculum.
- To motivate SE students in studying the basic notions of semiconductor physics, we must first give them good reasons for the importance of these materials in the development of electronics, and hence of the electronic products that are part of their everyday environment. Also, the tasks proposed must be as appealing as possible, in order to attract the students' attention towards their study.
- The introduction to semiconductor physics requires reconstructing the programming of the subject without taking any of the rest of the content away, and staying within the available schedule of classes. This can be done by selecting only that content of matter and electricity which is indispensable for learning the new topic. The open nature of the curriculum has to be taken into consideration, and it is the teacher who will ultimately have to decide on the specific learning objectives that are most appropriate for his or her educational context.
- For the teaching of semiconductor physics to be as effective as possible, there needs to be appropriate coordination between the science and the technology teachers. Indeed, one will have to define what each area is going to teach of this material at the same time as establishing a direct connection

between the two sets of content.

Development of the content and its didactic treatment

Having presented the above criteria, we shall now describe the teaching sequence along with the didactic treatment of the content.

'Preliminary part'

Before initiating the teaching of scientific concepts, it is necessary to motivate the students in their study. In the present case, we try to let them understand the importance of semiconductor materials in the development of electronics. Generally, this fact has already been stressed in technology classes, although then one usually goes on directly to the study of the operation and applications of different basic electronic devices. Therefore, what we are aiming for in this preliminary part is to stimulate the students' curiosity about why semiconductors are so special, and what are the concepts and scientific laws that can explain it. One way to approach this in class is based on asking the students such questions as the following:

- What differences do you find between the calculators, computers, and other electronic devices that you use at the moment, and those that your parents used when they were your age? How have they evolved?
- Do you know what materials the integrated circuits of computers, mobile telephones, calculators, digital clocks, video-consoles, etc., are manufactured from?
- Have you heard of semiconductors? Do you know anything about these materials?

To help the students respond to these questions, we encourage them to: (a) consult encyclopedias, popular science books, or Web sites dedicated to old and modern instruments of electricity and electronics; (b) ask their older relatives for information. They also read in class an article (Weisbuch, 2001) —which is intelligible for them— referring to the 2000 Physics Nobel Prize; which recognized the contribution of semiconductors to the development of electronics, in particular, and to the information age, in general. We also encourage debate and reflection on how the scientific and technological advances achieved with semiconductors have given rise to a progressive increase of the utility and performance of electronic devices.

Whatever the case, the intention is to motivate the students to learning some of the scientific concepts and phenomena associated with semiconductors.

'First part: Intrinsic semiconductors'

Once the importance of semiconductors has been made clear, the conceptual content is introduced. We begin with the study of intrinsic semiconductors.

– *Definition of intrinsic semiconductor*

At 14–15 years old, the students are already familiar with the periodic table of elements and the principal properties of the representative elements, and can distinguish metals and non-metals. They know that metallic materials are electrical conductors and non-metals are insulators. In this context, allusion is made to semi-metallic elements as being those which have properties intermediate between metals and non-metals. This leads into the introduction of the concept of a pure [intrinsic] semiconductor as a material consisting of a semi-metal, usually Si or Ge, which at room temperature has electrical properties intermediate between the typical conducting and insulating materials.

– *Internal structure of an intrinsic semiconductor*

At this level, we think that the most appropriate manner of representing the structure of intrinsic semiconductors is by means of the two-dimensional model of Figure 1. This is a simplified classical model representing the covalent structure of an intrinsic semiconductor [of Si or Ge] which permits a first introduction to the study of these materials in SE. It is also coherent with what is suggested in the SE science curriculum, which recommends the study of the structure of matter from a classical perspective, with the aid of plane

diagrams for its representation [e.g., Lewis diagrams of the covalent bond]. The uses of other more complex models, such as that of energy bands, would pose major difficulties for students at this educational level, since such models are based on quantum mechanics which is not introduced until the post-obligatory SE stage [16–18 years of age]. Also, according to recent research (Wittmann, Steinberg & Redish, 2002), even undergraduate students have difficulty in understanding the energy band model.

Figure 1. Two-dimensional model of the structure of an Si/Ge intrinsic semiconductor.
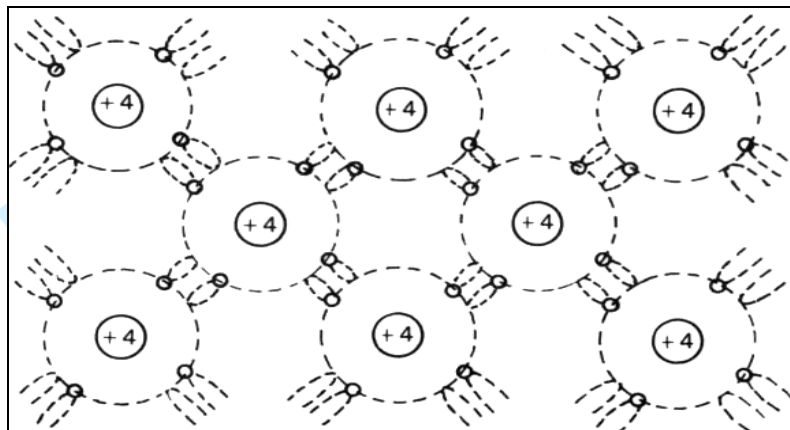
At the SE level therefore, with the octet rule as a basis and identifying the valence electrons, the students can verify that the atoms of the semiconductor represented in Figure 1 is stable. Each atom shares its 4 valence electrons with its 4 nearest neighbours, thereby reaching the electronic configuration of a noble gas.

– *Electrical behaviour of an intrinsic semiconductor*

The concept of resistivity is fundamental to understanding the electrical behaviour of materials, in general, and of semiconductors, in particular. Resistivity and its variations with temperature can be understood by SE students on the basis of three fundamental topics of the current science curriculum: the kinetic theory of matter, the concept of ionization energy, and the type of bond [metallic or covalent]. With this the students have the sufficient basis to can acquire a first idea of why the resistivity of a conductor increases with temperature while that of a semiconductor decreases.

In the case of a solid material, kinetic theory explains how the vibrational motion of its atoms or molecules around their fixed or equilibrium points is related to the temperature. This idea, besides forming part of the content studied by SE students, is usually well assimilated by them. Indeed, SE students are already able to relate the agitated motion of the particles of a material to its temperature. With this conception, one hopes that the students will be able to understand that metals [which have free electrons at low temperatures] turn into bad electrical conductors at high temperatures because the amplitude of the vibration of the atoms around their equilibrium positions increases, thus hindering the movement of the great quantity of free electrons. In semiconductors [atomic covalent solids], however, whose charges are fixed, an increase in temperature produces ruptures in their bonds, and consequently electrons are released when they acquire the energy of ionization, and will thus be available to form an electric current if the corresponding voltage is applied. This explains the decrease in resistivity of semiconductors with increasing temperature.

What we have just said about the liberation of electrons in the covalent lattice of a semiconductor allows one to make a first introduction to the concept of hole. In the context of the classical and simplified model of semiconductor that we are using, a hole can be defined as the vacancy that is left by an electron liberated from the lattice (Pierret, 1994).

Also, the kinetic theory and the concept of ionization energy allow one to make a first introduction to two essential processes in semiconductor physics: the generation and recombination of electron-hole pairs. Our aim is for the students to understand that when the electrons shared by the atoms in the lattice have acquired sufficient energy to break the bond, they become free electrons, and leave a vacancy [hole] in the lattice [Figure 2]. Usually it is relatively easy for the students to deduce that a hole appears for each electron liberated from the lattice, and that in an intrinsic semiconductor there will always be the same number of free

electrons and holes.

Figure 2. Generation of an electron-hole pair.
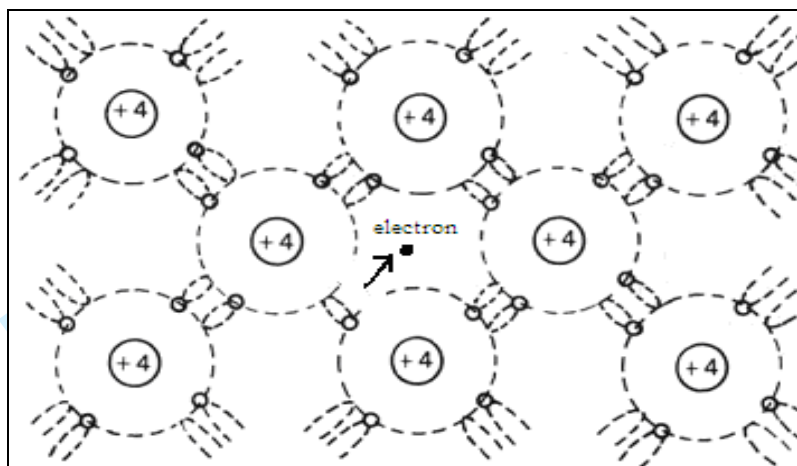
Assuming that the students already have in mind that a material is a good conductor if it has many free electrons, it is hoped that they understand that the generation of many electron-hole pairs converts the semiconductor into a good conductor of electricity. It is necessary to insist that this situation occurs at high temperatures —to give them specific data, they can be told that Si begins to be a good conductor at 600K. In this context, a brief reference is made to the application of semiconductors in the generation of photovoltaic energy. Our intention here is for the students to acquire a basic idea of the application, understanding that sunlight provides the ionization energy necessary to release electrons from the covalent structure, and that these can then form part of an electrical current. An example of question used to analyze the influence of temperature on the electrical behaviour of semiconductors is set next:

A team of scientists has been asked to study how the variation of temperature [T] affects the electrical conduction of a conductor [Cu] and a semiconductor [Si]. To this end, they measured how the resistivity [ρ] of the two materials varied with temperature. The results were represented qualitatively by the two graphs of Figure A. Now you try to interpret those results by answering the following questions:
a) How does the capacity to conduct electricity of Cu and of Si vary with temperature?
b) Which of the two substances conducts electricity better at high temperatures? Why?
c) In view of how the electrical conductivity of semiconductors varies with temperature, what applications might these materials have?

Figure A. Variation of resistivity with temperature: (a) sample of Cu, (b) sample of Si
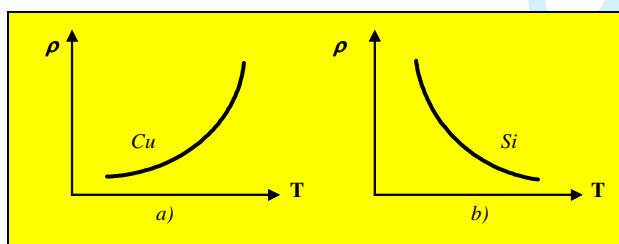
With respect to the process of the recombination of electron-hole pairs, the aim is for the students to understand that the free electrons lose part of their energy due to multiple collisions with the crystal lattice of the semiconductor. They then become bound again to the lattice atoms, occupying the holes left by other liberated electrons.

    – *Semiconductor charge carriers: Electrons and holes*

Our 14–15 year old students already have a first idea of Ohm's law and the physical magnitudes involved [current, voltage, and electrical resistance]. They also know that the electrical charge carriers in conductors

are electrons. The novel aspect introduced in studying semiconductors is that, in addition to the electrons, there is another type of charge carrier: the hole.

Previously we have defined the hole as the vacancy left by an electron liberated from the covalent lattice of the semiconductor. Also, in semiconductor physics, the hole is assigned a series of corpuscular properties in order to make it easier to understand electrical conduction in these materials. Holes behave as particles with the same properties as electrons except that they carry a positive charge [FOOTNOTE i]. Hence, if a voltage is then applied to the semiconductor, the holes 'generate' a positively charged electrical current that flows in the opposite direction to that of the electrons [Figure 3].

Figure 3. The movement of electrons and holes in a semiconductor.
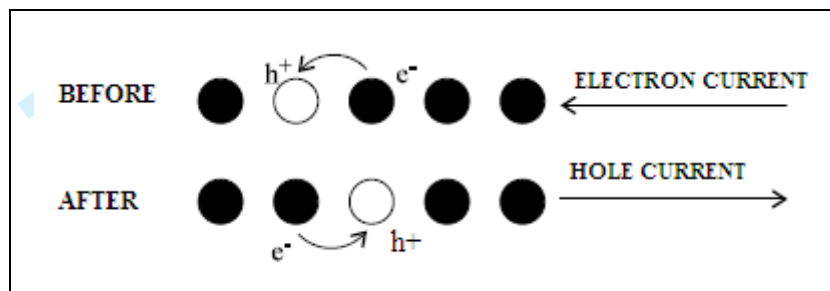
The concept of hole can be difficult for SE students to understand, mainly because their feeling of common sense leads them to reject the idea that something 'empty' functions as an electrical charge. After all, as Van Zeghbroeck (2004) says, electrons are the only real particles available in a semiconductor. Indeed, the holes only exist within the semiconductor. Unlike electrons, we 'will never be able to extract them from the material'. Pierret (1994) says that this type of mental conflict is usually a consequence of the imperfections, or limitations, of the models that we use in science. Nevertheless, in science teaching we have to take these limitations into account, and try to find the most suitable forms of presentation for the concepts to be comprehensible for the students.

With the complementary use of analogies, SE students can acquire an approximate idea of the concept of hole. We assume, for example, that we have six paper cups and five balls. Line the cups in a row, and put balls in the five rightmost cups. Now move the ball in the second cup to the first, the ball in the third to the second cup, and so on. It appears that the empty cup is moving to the right when, in reality, the balls are merely shifting to the left. Of course, this movement is possible because of the different number of cups and balls. Therefore, when this analogy is used, we previously clarify to the students that, although it may be a suitable way of illustrating the movement of the holes, it is really not a valid representation of an intrinsic [pure] semiconductor. The reason is that in the analogy there are not the same numbers of cups ['holes'] and balls ['electrons']. Obviously, being an analogy, it has its limitations with respect to the real situation of a semiconductor, but we find it to be very useful when the concept of hole is introduced in class. In our opinion, what the teacher must assess is whether the use of analogies such as that described above provides more advantages than disadvantages for the students' learning. For that reason, we are in favour of each teacher supplying the analogy most appropriate for his or her students.

As we observed above, considering the hole as a charge carrier is a consequence of the models that are used to facilitate understanding of the electrical behaviour of a semiconductor. The utility of the concept of a hole is easy to explain in terms of the energy band model [FOOTNOTE ii]. Since, however, SE students —at least in Spain— have no knowledge of quantum physics, we can not use the arguments provided by this quantum mechanical model at this educational level.

In the context of the proposed two-dimensional classical model of a semiconductor, we use the previous analogy to explain to SE students why the concept of holes is so useful. Let us imagine that we have many empty cups and only a few balls that are continually jumping from one cup to another. In this case, it is easy to follow the movement of the balls ['free electrons']. If, however, there are many balls and only a few empty cups, it is far easier to follow which cups are empty ['holes'] than to try to keep a record of the movement of all the balls.

We also anticipate that the assignment of a positive charge to the holes can give rise to cognitive conflicts in the students, because they may confuse them with protons. Two fundamental differences are therefore

stressed: (1) the protons are real charges and the holes are not, (2) whereas the holes can move and generate electrical current, the protons can not as they are inside the atomic nuclei.

'Second part: extrinsic semiconductors'

Once intrinsic semiconductors have been dealt with, extrinsic semiconductors are introduced. One begins by alluding to the limitations of the former, such as that they only conduct electricity well at high temperatures. The idea then naturally comes up that the scientists and technologists who were designing electronic devices needed to adapt these materials in some way so as to improve their performance. In particular, they wanted these materials to be able to conduct electricity well at room temperature. There thus arises the concept of extrinsic semiconductors.

Since SE students at this level already distinguish between pure and impure substances, an extrinsic semiconductor can be defined as a semiconductor which has been doped with impurities in order to improve its electrical conduction without raising the temperature [FOOTNOTE iii].

Before approaching the process of doping a semiconductor, the students are asked if they have heard the word 'doped' before [for example, they may have heard it to do with the realm of sport]. When the students have a general idea of what 'doping' is, they are asked if they know what impurities would have to be introduced into a semiconductor to modify its number of charge carriers [electrons or holes]. To help them answer, they are given the clue that the carriers will come from the valence electrons of the atoms introduced. What one hopes for is that the students draw the conclusion that doping a semiconductor consists of introducing atoms of elements different from those comprising the semiconductor, with a different number of valence electrons than Si or Ge.

Once the students have been able to associate the doping process with the introduction of foreign atoms, they are asked if the logical thing would be to introduce any type of atom whatever or if there should be some sort of restriction. They could be given a first clue: that the atoms introduced should not break, or significantly alter, the crystal structure of the material. We try to get the students to deduce that the impurities introduced should have a size similar to that of the atoms of the semiconductor [Si/Ge]. The clues they are given will help them reach the conclusion that this is achieved by introducing pentavalent or trivalent atoms, i.e., with one more or one less valence electron, respectively, than Si or Ge [tetravalent atom]. All of this is done before actually analyzing the effects of these impurities on the electrical conduction of semiconductors, and of course it is advisable that the students identify the elements with 3 and 5 valence electrons in the periodic table.

Figure 4. Generation of a free electron by means of the introduction of a donor impurity.
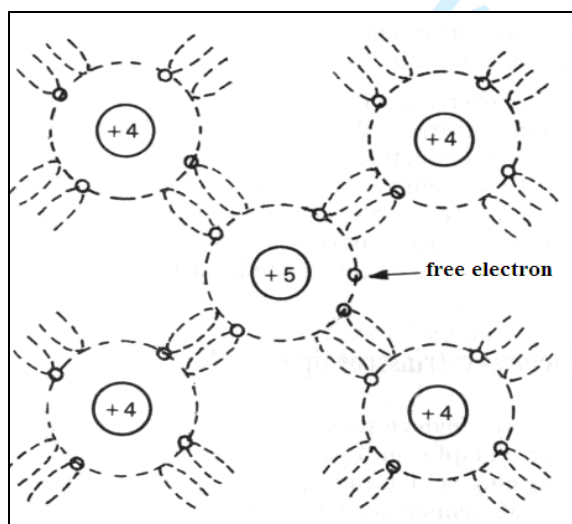
After the students have identified the usual impurities with which semiconductors are doped, the next objective is that they understand the consequences for the latter's electrical behaviour. This is achieved using the two-dimensional model of a semiconductor [Figure 1], and the octet rule. The students are asked what happens if a pentavalent atom, Sb for example, is put into a Si/Ge semiconductor [Figure 4]. One hopes that the students are able to see that this impurity shares four of its valence electrons with each one of four

neighbouring atoms of Si/Ge, leaving one of its electrons unpaired. Then they are put the following generic question: Does this 'surplus' electron, which is not involved in the covalent bond, require a liberation energy that is equal to that required to break a covalent bond? The students are given the information that even at room temperature this electron can acquire sufficient energy to become a free electron. The intention is that the students understand that with the introduction of pentavalent atoms into a semiconductor one is able to have free electrons without the corresponding holes. And then, when a voltage is applied, the current due to electrons will be greater than that due to holes.

The students are next asked to investigate what the impurities that generate free electrons in a semiconductor without the corresponding holes are called. The intention is that they find that these impurities are called donor impurities [pentavalent atoms]. This in addition allows one to define the concept of n-type [for negative] extrinsic semiconductor as one which has been doped with donor impurities, and that therefore has electrons as majority charge carriers.

Analogously, the students are next requested to analyze what happens when a semiconductor is doped with trivalent atoms. They are expected to deduce that the 'foreign' atom [impurity] does not have enough valence electrons to complete the four covalent bonds. Consequently, a hole appears in one of the bonds [Figure 5] without any electron having been liberated. They will also be asked to find out what the impurities that generate holes in a semiconductor without the liberation of an electron are called. In this case, one hopes that the students will find that these are called acceptor impurities [trivalent atoms]. What is really intended is that they get to understand that doping a semiconductor with acceptor impurities increases the concentration of holes with respect to that of electrons, and also that the majority charge carriers are now holes [positive] so that the semiconductor is called a p-type [for positive] extrinsic semiconductor [FOOTNOTE iv].

Figure 5. Generation of a hole by the introduction of an acceptor impurity.
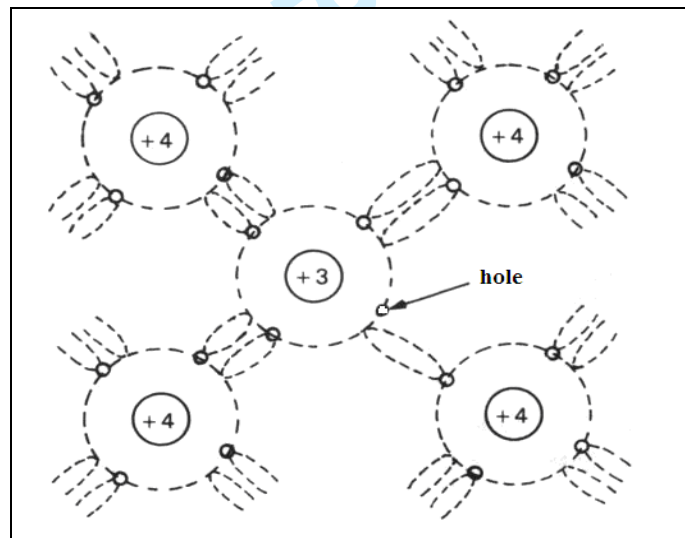
One possible source of difficulty of comprehension can be that there are different quantities of free electrons and holes in the extrinsic semiconductors. This may lead the students to think that they are not electrically neutral. In this sense, the students are asked how the quantities of electrons and protons of a semiconductor will vary when it is doped. The intention is to reinforce the idea that the impurities, whether donors or acceptors, that are inserted into a semiconductor are atoms, and that they therefore contribute the same number of electrons and of protons to the semiconductor. Therefore, although the inserted atom [impurity] is itself left ionized when it occupies the site of a Si or Ge atom, the semiconductor continues to be neutral. If necessary, as supplementary information, we indicate to the students that these ions [positive if they are from donor impurities or negative if from acceptor impurities] do not contribute to the electrical conduction since they occupy fixed positions in the crystal lattice and do not move. Otherwise, this would mean the rupture of the material (Pierret, 1994).

Strategies for analyzing the effectiveness of the teaching sequence

It is no easy task to analyze the effectiveness of a teaching sequence considering how complex the educational process is, with the many interacting variables related to the content to be taught, to the characteristics of the students, the group-class, and the teacher, to the sociocultural context, etc. As the present case corresponded to the first steps of an innovatory teaching sequence, we decided to centre the analysis of its effectiveness on:

1. *Evaluating the levels of knowledge of semiconductor physics acquired by the students in terms of the predicted learning objectives*. In our opinion, this would give an idea of what SE students are capable of learning about semiconductor physics through the designed teaching sequence.

2. *Identifying the students' commonest learning obstacles with respect to the topic*. The psychology of learning tells us that scientific reasoning does not seem to be the natural form in which people tackle their daily problems (Pozo & Gómez Crespo, 1998). Many of the students' intuitive ideas are usually developed at a very early age, generally before the learning of scientific notions begins (Rodríguez-Moneo & Aparicio, 2004). Therefore, these ideas are usually strongly rooted, and in many cases constitute true obstacles against learning science (Criado & Cañal, 2003). In the context of teaching models such as the one we are proposing, in which the students themselves are considered to construct their own knowledge from their interactions with the teacher and classmates [the 'socio-constructivist' model], the identification of these obstacles is fundamental for the progressive improvement of a teaching sequence. In this regard, Martinand (1983; cited in Gómez-Molinély & Sanmartí, 2002, p. 63) suggests that if learning consists of overcoming the obstacles that one encounters while learning new ideas then these obstacles have to be explicitly targeted in teaching those ideas. From this perspective, Martinand introduces the concept of 'obstacle-objective', differentiating it from the classical concept of objective. He thinks that the true objectives in teaching science can not be defined *a priori* and independently of the students' conceptions, but will consist of strategies directed at overcoming the obstacles that are detected. Therefore, the identification of the students' learning obstacles with respect to semiconductors will be an important indicator as to which learning objectives will have to be reformulated to improve the effectiveness of the teaching sequence in future actions.

3. *Determining the attitudes that the students develop towards semiconductor physics and its learning*. It seems evident that if the teaching sequence can arouse the students' interest in the topic —whether from the scientific content being studied, from the manner in which it is approached in class, or both— then this will be more favourable for the learning process.

4. *Assessing to what extent the teaching sequence fosters the students' self-regulation of their learning*. In agreement with Millar (1989) and Viennot and Rainson (1999), in teaching science one must not only pay attention to what to teach, but also to how to teach. In this sense, we think that a good indicator of the effectiveness of a teaching sequence is the [qualitative] measure to which it encourages the students to learn to regulate their own learning. Indeed, self-regulation of learning is today conceived of as a fundamental practice for the meaningful learning of science (e.g., Schraw & Brooks, 1999). And, in addition to the teacher's interventions and interactions between the students, this practice can be helped by a suitable design and organization of the activities within the sequence.

In order to analyze the above aspects, we used a variety of research procedures and instruments, as it will be seen below.

Research questions

Given this context, we formulated the following questions in order to analyze the effectiveness of our teaching sequence:

1) What levels of knowledge of semiconductor physics can SE students attain with the designed teaching sequence? With respect to which concepts are the levels reached most satisfactory?

2) Which are the students' main learning obstacles with respect to the semiconductor physics content studied?

3) Does the teaching sequence favour a climate of cooperation among the students and their practices of self-regulation? How do these practices contribute to the students' learning?

4) What attitudes do the students acquire towards semiconductor physics and its learning?

5) What will we be able to do to improve the effectiveness of the teaching sequence in subsequent applications?

Method

Participants

This pilot study was carried out over the course of two academic years in a secondary school in Seville [Spain]. Two classes of 3rd year SE students [14–15 years old] participated in the study. In order to perform the study in a natural context of teaching practice (Elliott, 2000), the participant students were those whom one of the authors was instructing in Science [Physics and Chemistry] and in Technology. In the first academic year, 33 students participated, and in the second, 27 students, for a total of 60 students. The two groups had a similar prior cognitive baggage. Two sorts of data supported this assumption: (1) the observations made by the teacher who was responsible for the implementation of the teaching sequence, and (2) the school's evaluation reports on the academic performance in general, and on that of science in particular, of the preceding school years for the two groups of students involved.

Implementing the teaching sequence in the classroom

The teaching sequence was applied after the students have studied the content relative to matter and electricity, which will form the fundamental support for the new learning. The implementation is by means of a sequenced set of interconnected activities in order of increasing difficulty. Table 1 gives an overview of the teaching sequence.

Table 1. General overview of the teaching sequence.

Class sessions	Content studied	Activities	Learning objectives
1	What is the presence of semiconductors in our everyday lives?	A.1	1.1 To recognize the role of semiconductors in the progress of scientific knowledge in electronics.
			1.2 To feel curiosity about the behaviour and physical properties of semiconducting materials.
2, 3, 4	What are so-called semiconductors? Which materials are semiconducting?	A.2–A.5	2.1 To recognize an intrinsic semiconductor as a material consisting of semi-metallic elements [Si or Ge] that normally has an electrical behaviour intermediate between conductors and insulators.
5, 6, 7, 8	At a microscopic level, how does one explain the mechanism that allows electrical conduction in semiconductors?	A.6–A.12	3.1 To understand, with the aid of the octet rule, the covalent solid structure of a Si or Ge semiconductor.
			3.2 To recognize and draw the covalent solid structure of a semiconductor by means of a model of two-dimensional bonds, similar to plane Lewis diagrams.
			3.3 To understand that at high temperatures metals have a surplus of free electrons, and that there is an increase of the vibrational motion of the atoms of the metallic structure around their equilibrium positions, thus hindering the circulation of free electrons [high electrical resistivity].
			3.4 To understand that intrinsic semiconductors become good conductors of electricity at high temperatures – better even than typical conductors – because the bonds of the semiconductor's covalent structure break and release valence electrons which can then carry electrical currents [low electrical resistivity].
			3.5 To understand that each electron liberated from the covalent structure of a semiconductor leaves a vacancy, called a hole [generation of electron-hole pairs].
			3.6 To understand that when the liberated electrons lose their energy, they fall back into the covalent structure occupying the holes left by other liberated electrons [recombination of electron-hole pairs].
			3.7 To see the utility of semiconductors in the production of photovoltaic energy.
			3.8 To acquire a rough idea of the main properties of holes: (a) they are carriers of

				positive charge; (b) their motion is in the contrary direction to that of free electrons; and (c) they are fictitious particles that are defined to get a simple explanation of the electrical behaviour of semiconductors.
			3.9	To see electrons and holes as the charge carriers in a semiconductor.
			3.10	To understand that a voltage applied to a semiconductor produces a negative electrical current [due to free electrons] and a positive current [due to the holes].
			3.11	To understand that in an intrinsic semiconductor there are the same number of free electrons and holes.
			3.12	To use and interpret analogies aimed at explaining the behaviour of a semiconductor's charge carriers.
9, 10, 11	How can semiconductors be modified to improve their electronic and electrical properties?	A.13–A.20	4.1	To understand that the purpose of doping a semiconductor is to control and improve its electrical conduction at room temperature.
			4.2	To understand doping a semiconductor as a process that consists of introducing impurities – atoms of other elements with a similar size to that of the atoms that make up the semiconductor.
			4.3	To understand that the introduction of impurities into a semiconductor unbalances the equilibrium between the positive and negative charge carriers:
				(a) Donor impurities [pentavalent atoms] increase the number of free electrons with respect to that of holes: n-type extrinsic semiconductor.
				(b) Acceptor impurities [trivalent atoms] increase the number of holes with respect to that of free electrons: p-type extrinsic semiconductor.

As it is shown in Table 1, the complete implementation of the sequence requires eleven 1-hour class sessions. For that reason, the scheduling of the subject of Physics and Chemistry in the 3rd year of SE made it necessary to reconstruct its programming. Taking advantage of the flexible character of Spain's SE science curriculum, we decided to reduce the content relative to the study of matter and electricity. Of these two topics, we selected only that content which was essential for the subsequent learning of notions of semiconductor physics. Consequently, the students would study the unselected content on matter and electricity in the next academic year [4th year of SE, aged 15–16] with the same teacher.

For the activities, the students organized themselves into groups of three or four, the aim being to foster cooperative learning. Within each group, they interpreted the information presented in the activities, exchanged ideas, looked up information together [in the library and on Internet], and prepared a consensus answer to the questions posed. Then, in the whole-class sessions, each group presented its conclusions to the rest of the groups in order to discuss them and try to arrive at the best answer with respect to the foreseen learning objectives. The teacher moderated these discussions and introduced the opportune orientations in order that a conclusion could be reached with the greatest possible agreement [in terms of understanding]. This process was fundamentally an attempt to show the students the explanatory limitations of mistaken or imprecise ideas, and how other arguments [accepted scientifically] permitted a better explanation of the phenomena and situations being analyzed.

The implementation of the teaching sequence also included strategies for the development of the students' capacity for self-regulation. The aim was for them to become aware of both the difficulties they encountered and their real progress so that they could learn to control their own learning. In effect, the idea was that they should learn to learn. As part of the self-regulation process, the students recorded in their notebooks comments and reflections about their experience with each activity in the sequence. We shall go deeper into this below.

In order to obtain data as reliable as possible for the study, the teaching sequence was implemented under the same conditions in both years, i.e., same teacher, same number of class sessions, same term [the 2nd trimester], and same starting point for the instruction. Also, the students of both groups had studied the same prior content on electricity and matter with the same methodological approach, and again with the same teacher.

The research process and its instruments

Given that the main aim of the study was to analyze the effectiveness of a teaching sequence [students' ideas, learning obstacles, attitudes…] in a particular educational context, the research and the analysis methods used were qualitative. Data triangulation was performed by means of three investigation instruments,

as it will be seen next.

(a) Test

A test [Appendix] was designed to analyze the levels of declarative knowledge attained by the students, and to discover the main obstacles they faced in learning the topic. The aspects covered in the test are listed in Table 2. The first four items were multiple choice, with the students adding a justification for their answer. The aim of it was to obtain data on the students' ideas and reasoning. The other four items were open in form, the aim being to go deeper into their ideas on the concepts and phenomena involved, since in this type of item it is the student who independently sets the limits to the answer.

Table 2. Conceptual content involved in the written test of evaluation.

Items	Scientific notion involved
1	Electronic configuration of the atoms of a semiconductor, and its behaviour at room temperature
2	Variation of the resistivity of an intrinsic semiconductor with temperature
3	Concept of hole
4	Process of generation and recombination of electron-hole pairs
5	Generation of a free electron in a semiconductor by means of doping
6	Concept of a p-type extrinsic semiconductor
7	Charge carrier balance in an n-type extrinsic semiconductor
8	Electrical state of an extrinsic semiconductor

The first version of the test had numerous items, selected according to the anticipated learning objectives, and covering all the content of the teaching sequence. The items were designed to allow a classification of the students' answers, and hence determine the levels of knowledge attained. The next step was to reduce the number of items. Following Pérez-Juste (1989), to this end we sought the opinions of colleagues who are expert teachers of semiconductor physics. With their aid, we decided which items needed to be modified or eliminated. After applying the test, we eliminated from the subsequent analysis those items which did not really contribute any interesting data on the knowledge acquired by the students, in the sense that they did not help in the classification process. The analysis was thus reduced to the eight items given in Appendix.

The data were analyzed by means of an inter-judges agreement procedure (Walker, 1992). In this, the researchers [two, in our case] analyze the data independently, and then together contrast the results. Agreement on the most suitable value to assign is reached in those cases in which the data do not coincide.

(b) Personal interviews

In order to triangulate the test data, and thus to study in further depth the students' ideas and modes of reasoning, we conducted personal interviews on the same topics. The method used was the directed interview (Padilla, 2002). In this method, the interviewers introduce more explicit pointers into their part of the procedure in order to activate richer and more specific information. Nonetheless, all the interviews followed the same script of questions in accordance with the items in the test. Also, the criteria for classifying the responses and the method of analysis were the same as used with the test. Each interview lasted around 20 minutes.

Even though we had taken especial care in preparing the interviews, we considered it advisable to conduct preliminary trials. The intention was to refine the process and appropriately channel the questions with respect to situations that might produce some type of bias in the information.

The interviews were also aimed at determining the students' opinions and assessment of this particular teaching-learning process. The purpose was to evaluate the attitudes that they had developed towards semiconductor physics and its learning, and the principal conceptual and methodological obstacles that they had encountered during learning.

(c) Monitoring the students' self-regulation of their learning

The aim of the teaching sequence was not only for the students to learn notions of semiconductor physics, but also that they learned independently and with self-reliance, that they construct their own body of knowledge in interaction with their classmates, and that they can endow what they learn with meaning (Ibáñez & Gómez-Alemany, 2005). To this end, the teacher helps them to develop strategies for planning and monitoring their own learning. In this context, the concept of self-regulation of learning arises. Today, learning based on self-regulation is regarded as fundamental for the construction of scientific meaning (Ayensa, 2001; García-Carmona, 2005; Moore, 1999; Schraw & Brooks, 1999).

The goal of getting the students to practice self-regulation strategies during the implementation of the teaching sequence was also evaluated. Before initiating the study, we had already devoted some class time to teaching them to write in their notebooks a reflective commentary on what they had learned during a class activity. In these notes, the students indicated the corrections that had been made, the difficulties encountered, the aid received from companions or the teacher, their own assessment of how their learning had evolved over the course of the activity, etc. All the students had to structure these commentaries following a common protocol that we had established previously. Thus, the first thing they had to note was their initial answer to the questions posed in the activity, then any corrections or additional comments made to that initial answer, together with what type of cause had motivated this modification [their own reflection, a classmate's explanation, teacher's involvement, the whole-class session at the end of the activity, etc.]. As a final reflection, the students had to give a self-evaluation of the learning they had attained in the activity. In this last point, we aimed for the students' explanations to be as homogeneous as possible so as to facilitate the subsequent analysis. To help them, we suggested that they should use such phrases as the following: "At the outset I believed …, but soon I understood that …"; "After the whole-class session, I understood that …"; "After the discussion in class, I still don't really understand …"; "Help from and discussion with classmates helped me to understand that …"; etc. This allowed us to classify the students' self-assessed levels of learning in each activity of the sequence, following a pre-established categorization that will be described below.

We must stress that we are aware that the students' valuation of their own learning may be subjective, i.e., that it does not really reflect the learning actually attained. Among other reasons, their valuation may depend on each student's degree of self-confidence and/or how much they expect from themselves. Nevertheless, we think that these aspects are all an intrinsic part of the complex process of learning, and that it is the student — rather than the teacher— who has more clues to how his or her learning is progressing. This is especially so when the students are accustomed to making an ongoing meta-reflection on their own learning process. Also, we believe that the modifications or corrections that the students note in their commentaries can be taken as more or less objective data, and can contribute to their becoming aware of how their learning is going and what they can do to successively improve the process.

Results and analysis

The students' levels of knowledge and their commonest learning obstacles

(a) Results of the test

To describe and analyze the declaratory levels of knowledge that the students presented in their responses to the test, we established categories or levels of answer according to the scientific knowledge involved. Initially we allowed many levels, but found that this not only made the process of classification difficult but neither did it provide a clear hierarchical order of the responses. Therefore, as the study progressed, we grouped levels together according to the similarities that we observed. We finally defined an ordinal scale of four levels of response. The definitive classification criteria were the following:

- Level 1: Response left blank.
- Level 2: Incorrect or confused response, in the sense that it does not adequately apply or understand the concepts.
- Level 3: Response in the correct line, but is justified incompletely or with certain inaccuracies.
- Level 4: Correct response and justified adequately according to the pre-selected objectives.

As we indicated above, the responses to the test were analyzed independently by the two researchers. Each one classified the different responses according to the levels established, and then these levels were compared. The percentage of inter-judges agreement was 91.6%. In the cases of discrepancies [the remaining 8.4%], consensus was reached as to the appropriate level to assign. These discrepancies arose mainly in whether to classify responses to Levels 3 or 4.

In order to estimate of the global level of knowledge shown by the students, we used the median score for each item given the ordinal character of the scale. We observed that for all except Item 8 the level was around a value of 3. Given the meaning of this level in the above classification, the interpretation is therefore that the students in general had acquired scientific ideas and arguments in the appropriate line, although with certain mistakes and inaccuracies with respect to the ideas accepted scientifically. Table 5 shows the percentages of the levels of response attained by the students in each item of the test, and accumulated percentages at higher levels [Levels 3 and 4].

In the following, we describe and analyze in detail the students' most usual ideas and obstacles with respect to the aspects of semiconductor physics dealt with in the test.

Table 5. Percentages of the levels of response attained by the students in each item of the test, and accumulated percentages at higher levels [Levels 3 and 4].

Items	Level 1	Level 2	Level 3	Level 4	(Level 3 + Level 4)
1	8.3	18.3	48.3	25.1	73.4
2	13.3	48.3	15.1	23.3	38.4
3	6.7	40.0	30.0	23.3	53.3
4	11.7	20.0	26.7	41.7	68.4
5	18.3	16.7	21.7	43.3	65.0
6	10.0	23.3	33.3	33.3	66.6
7	6.7	30.0	23.3	40.0	63.3
8	10.0	61.7	8.3	20.0	28.3
(n=60)					

'Electronic configuration of an intrinsic semiconductor and its behaviour at room temperature'

With Item 1, the idea was to see whether the students were able to recognize a semiconducting material from the electronic configuration of its elements, and to explain its electrical behaviour with reference to the valence shell. We found that somewhat more than 8% of the students left their response blank [Level 1], and around 18% responded inadequately [Level 2] in the sense that they thought the intermediate electrical behaviour of semiconductors at room temperature is because they simultaneously have properties of conductors and insulators [conductor-insulator duality]:

Level 2: "[…] because it is a semiconductor, so that it is half insulator and half conductor, then it is a better conductor than the insulators and a worse conductor than the conductors."

For the higher levels, around 48% scored Level 3 [no more than descriptive responses], and about 25% Level 4 [in which the responses were interpretatively appropriate based on atomic theory]. Examples of the responses of these levels were:

Level 3: "I have chosen this option [*Option (c)*] because it is a semiconductor and, according to what was studied, as it has an intermediate behaviour it is a better conductor than non-metals and a worse conductor than metals." [Italics added]

Level 4: "I choose Option (c). The element is a semiconductor because it has 4 electrons in its last layer. Since to be stable it is equally easy or difficult for it to lose them as to gain them, its electrons do not move with as much freedom as in the conductors nor are they as stuck as in the insulators."

'Electrical behaviour of an intrinsic semiconductor at high temperatures'

The students' understanding of the variation of the resistivity of an intrinsic semiconductor with temperature

was analyzed by means of Item 2. We found that around 13% of the students did not know what to respond [Level 1], and nearly half responded incorrectly [Level 2]. We detected the idea of uniformity in the electrical behaviour of different types of materials, in particular, that the behaviour of a semiconductor is the same as that of a conducting material at high temperatures:

> Level 2: "I believe that it is Option (c). If you raise the temperature of a semiconductor, it has many free electrons and they get in each other's way, so that it conducts badly electricity, and becomes an insulator."

> Level 2: "It is Option (b) because at high temperatures the atoms of all materials are very agitated and the free electrons collide with them, which hinders their mobility."

Also in Level 2, we found that the students confused the cause-effect relationship between temperature and resistivity in a semiconductor:

> Level 2: "It is Option (a) because the semiconductors when they have greater resistivity diminish their temperature […]."

Around 15% of the students scored Level 3, and somewhat more than 23% Level 4 where again there were appropriate explanations of the relationship between temperature and electrical behaviour.

> Level 4: "The response is (a). If we increase its temperature, its bonds will be broken and the electrons will be freed, which will allow better conduction of electricity. At normal [*room*] temperature the electrons are very united [*bound*]. In the metal, when the temperature increases, there also happens the same, electrons are freed; but at room temperature it already has many free electrons, and if even more are freed [*as the temperature rises*], a collapse will be created and electricity will not be conducted well." [Italics added]

'Concept of hole'

The students' conceptions of the concept of hole were studied by means of Item 3. The lowest levels of responses were around 7% for Level 1, and 40% for Level 2. The most frequent obstacle was in being able to accept the assumption that holes are assigned a positive charge.

> Level 2: "Holes do not have electrical charge because in reality a hole does not exist and therefore it does not have charge."

> Level 2: "Holes do not have charge, it is the electrons and the protons which have it; what happens is that when an electron is freed, it leaves its hole in the bond […]."

Another obstacle was that the students think that the hole still exists after the recombination process has taken place, as if were a sort of 'holster' or 'housing' for the electron that acquires the latter's charge:

> Level 2: "The holes do not have an electrical charge, but when they are occupied by electrons they take their charge."

> Level 2: "The holes by themselves do not have an electrical charge, the only charge that they acquire is that of the electron that occupies it […]."

Some 30% of the students scored Level 3. These students accept that the holes carry a positive charge, but they do not justify it appropriately. For example, some students indicated that the positive charge of the hole comes about because the free electrons fall into the holes when the recombination process takes place, i.e., they think that the recombination process is like an electrostatic interaction of two opposite charges:

> Level 3: "I believe that they have a charge, and in addition it is positive, because like that, in the recombination process, it attracts electrons, since if it were negative, it would repel electrons."

> Level 3: "The holes have the same charge as the electrons, but of positive sign, since the electron occupies the site of the hole, then they attract each other; charges of different sign attract each other and get bound."

Somewhat more than 23% of the students scored Level 4. An example response was:

> Level 4: "Usually one says that the holes have positive charge because they always go in the opposite direction to the electrons (negative), but both have the same value of charge. That positive charge of the hole does not exist, but when you put at one end [*of the semiconductor*] a positive pole and at the other a negative pole [*application of a voltage*], the electrons will go towards the positive pole and the holes to the negative. For that

reason we say that they have a 'positive charge'." [Italics added]

'Generation of electron-hole pairs'

Although the students referred to the process of generation in the explanations they gave to the previous items, this phenomenon was studied explicitly in Item 4. Somewhat less than 12% of the students did not respond [Level 1], and some 20% did so inadequately [Level 2], although in this case we observed no predominant obstacle worthy of comment.

Almost 27% of the students scored Level 3. Some of them, although they indicated that an electron-hole pair appears in the generation process, did not clearly differentiate it from the recombination process:

Level 3: "In the process of generation there appears an electron-hole pair. It is the process in which a free electron passes to occupying a hole left previously by another electron."

Nearly 42% of the students scored Level 4. An example of the responses was:

Level 4: "In this process there appears an electron-hole pair in the semiconductor because the electron, on receiving the ionization energy, breaks the bond. By becoming free the electron leaves a hole in the bond, and thus an electron-hole pair is generated."

'Generation of a free electron in a semiconductor by means of doping'

Item 5 was targeted at investigating the ideas about doping with donor impurities. We found that around 18% of the students gave no response [Level 1], and almost 17% were mistaken [Level 2]. We observed that, besides confusing donor and acceptor impurities, the students did not understand the doping process properly. They thought that it is identical to the electron-hole pair generation process. Thus they think that, when a hole is generated by means of doping, a free electron is also obtained. This obstacle is brought out in the following explanation:

Level 2: "By putting donor impurities into it, holes are generated that will also produce free electrons. They are generated like in an intrinsic semiconductor."

Another obstacle detected was that the students think, in analogy to the case in the intrinsic semiconductors, that when a semiconductor is doped its temperature increases, and for that reason it becomes a good electrical conductor:

Level 2: "[…] because with doping the temperature rises and thus the resistivity falls."

We also observed that the students think that doping a semiconductor with donor impurities consists of directly introducing electrons. They even assume that the holes are a sort of 'defect' of the semiconductor's crystal lattice that has to be corrected by adding donor impurities:

Level 2: "Doping a semiconductor consists of putting in free electrons to fill up the holes that there are in a semiconductor."

Nearly 22% of the students scored Level 3. The incompleteness of their justifications lay in not sufficiently clarifying the characteristics that donor impurities must have:

Level 3: "Well if to an intrinsic semiconductor you add atoms of another material, with a greater number of valence electrons than the atoms of the intrinsic semiconductor, a free electron would be generated."

About 43% of the students scored Level 4, with appropriate justification of their responses. An example of this type of response is the following:

Level 4: "When we dope a covalent solid of germanium, for example with antimony atoms, we generate more free electrons than holes. This happens because antimony has 5 valence electrons and it can only share 4 with the germanium atoms that surround it; for that reason one is surplus that will become a free electron." [This explanation was accompanied by a two-dimensional diagram of the covalent structure of germanium.]

'Obtaining a p-type extrinsic semiconductor'

The target of Item 6 was to determine whether the students had understood how a p-type extrinsic semiconductor is obtained. Responses were left blank by 10% of the students [Level 1], and about 23%

responded mistakenly [Level 2]. One of the main obstacles observed was that the students think that the holes participate in the electrical neutrality of semiconductors as if they were real physical charges, in particular, that p-type semiconductors are positively charged:

> Level 2: "The p-type semiconductors are positively charged semiconductors, and the acceptor impurities are those that originate holes within the semiconductor. For that reason, having more holes than electrons, it will be charged positively."

A third of the students scored Level 3. The typical mistake in their justification, as was the case with donor impurity doping, was that the acceptor impurities are holes directly, and not trivalent atoms. Obviously, there is a similarity between the students who think that doping with donor impurities consists of introducing electrons directly [Level 2 of Item 5] and those who think that doping with acceptor impurities consists of introducing holes directly. Nevertheless, the context in which the latter was evidenced was different from that of the previous item, and the obstacle detected is –in our judgement– less significant than in the former, since the reasoning given by the students was close to the correct idea. For that reason, we scored it at Level 3. An example of the responses was:

> Level 3: "[…] because the acceptor impurities are holes and have positive charge, so by giving it acceptor impurities there are more positive charge carriers […]."

Another third of the students scored Level 4. An example of their responses is the following:

> Level 4: "[…] Acceptor impurities are introduced because they have 3 valence electrons; then, as the atoms of the semiconductor have one valence electron more [than this], when binding with the impurities holes are left in the structure of the semiconductor. So it has more holes than free electrons, and for that reason is called a p-type extrinsic semiconductor (p for 'positive')."

'Balance of charge carriers in an n-type extrinsic semiconductor'

Item 7 was targeted at analyzing the students' ideas about the charge carriers in an n-type extrinsic semiconductor. About 7% made no response [Level 1], and 30% scored Level 2. We again detected the idea-obstacle that an extrinsic semiconductor is electrically charged, and hence that an n-type semiconductor is negatively charged:

> Level 2: "… an n-type semiconductor has a greater number of electrons, which are negatively charged, and fewer holes, which are positive. Therefore, [*the semiconductor*] is left with a negative charge." [Italics added]

About 23% of the students scored Level 3, and 40% Level 4. An example of a Level 4 response is:

> Level 4: "The n-type semiconductors are formed by doping an intrinsic semiconductor with donor impurities (5 valence electrons). These give rise to a free electron and, for that reason, by having more free electrons than holes, it is said to be of type n (from negative). As it has more electrons than holes, one says that the first (the electrons) are the majority carriers and the holes the minority ones."

'Electrical state of an extrinsic semiconductor'

Item 8 was targeted at checking the students' conceptions about the electrical state of a semiconductor doped with impurities [extrinsic semiconductor]. This was the item that had the greatest percentage of inadequate responses. It was left blank by 10% of the students [Level 1], and nearly 62% responded mistakenly [Level 2]. The most significant obstacle —as was already detected in the previous two questions— was thinking that an extrinsic semiconductor is not electrically neutral, mainly because the students were thinking of neutrality in terms of a balance between the number of free electrons and holes:

> Level 2: "No, because if we introduce two donor impurities into an intrinsic semiconductor, two free electrons are generated, so there will be a greater number of electrons than of holes; therefore it does not continue being electrically neutral."

Also, they justify the electrical non-neutrality of an extrinsic semiconductor, as was already detected in Item 5, by identifying the donor impurities with free electrons:

> Level 2: "No, since that would change its configuration and it would become negative, because the donor impurities are electrons."

About 8% of the students scored Level 3, and 20 % Level 4. An example response of the latter category is the following:

> Level 4: "Yes, because although with doping the semiconductor has more free electrons than holes, as in this case, the number of electrons and protons continues to be the same; and that is what really matters for neutrality. The atoms (impurities) that are introduced are neutral in themselves, so the semiconductor will continue being neutral."

As a summary of these results, we would highlight the following observations. From the percentage of responses corresponding to Levels 3 and 4 together [Table 5], one deduces that the level of knowledge the students reached was moderately satisfactory and similar in the aspects measured by most of the items. There were two exceptions. The first, and most significant, was Item 8, about the electrical state of a doped semiconductor. The main obstacle detected was the belief that the semiconductor ceased to be electrically neutral. The second was Item 2, corresponding to the behaviour of a semiconductor at high temperatures. The students' conception of the microscopic mechanism was identical to that of a conducting material. We also found that the concept of hole [Item 3] created difficulties of understanding for the students. These three concepts gave rise to the students developing conceptions that competed strongly with those accepted scientifically.

(b) Analysis of the personal interviews

Interviews were carried out with 22 students, selected at random from the total of the participants in the study [n=60], two weeks after the conclusion of each school year's teaching-learning process. Recall that for the analysis of the interviews we followed the same classification criteria as were used for the responses to the test, including the inter-judges agreement procedure. The inter-judges agreement was 93.2%, and agreement was reached in classifying the other 6.8%.

We observed practically the same ideas and arguments as we had detected from the test. Furthermore, there was coherence between the responses given by the students in the interview and those that the same student had given in the test. This thus lent support to: (1) the existence of a pattern of conceptions and obstacles of the students with respect to the topic, and (2) acceptable validity and reliability of the test.

The observed order of difficulty of the content dealt with in the interviews was similar to that detected with the test. In particular, there stood out the difficulties related to the behaviour of semiconductors at high temperatures, to the concept of hole, and to the process of doping. As illustrations, we shall describe some of the most representative and interesting arguments and explanations that the students gave with respect to these aspects.

'Behaviour of a semiconductor with temperature'

Asked about the liberation of electrons in a semiconductor by varying the temperature, 14% of the students interviewed did not know what to respond [Level 1] and 23% gave a mistaken response [Level 2]. The latter again brought out the confusion the students have with respect to the cause-effect relationship between temperature and resistivity:

> Teacher: "Why does a semiconductor conduct electricity well at high temperatures?"
> Student: "The semiconductor as it's… as it's at room temperature it has few free electrons, so as the resistivity rises so does the temperature, so that more free electrons are produced, and holes as well […]."

Also the Level 2 responses reflected the mistaken conception that semiconductors have the same electrical behaviour as conducting materials relative to changes of temperature:

> Teacher: "Why does a semiconductor conduct electricity well at high temperatures?"
> Student: "It's not that. If we raise the temperature of a semiconductor it becomes an insulator. It's as if the electrons disappear and for that reason it is a worse conductor."
> Teacher: "Then, at low temperatures how does a semiconductor behave?"
> Student: "It becomes a good conductor […]."

Responses at Level 3 were given by 28% of the interviewees. The following is an example:

> Teacher: "Why is a semiconducting material a better conductor than a metallic material at high temperatures?"

Student: "Well it's because the metal when it is very hot can spoil. And semiconductors at high temperatures release more electrons and become better conductors."

Teacher: "Doesn't perhaps that last thing that you said happen also in metals?"

Student: "Yes, but metals spoil, and semiconductors do not; they become good conductors."

The highest level of understanding [Level 4] was expressed by 35% of the interviewees, with arguments similar to the following:

Teacher: "Why does a semiconductor conduct electricity well at high temperatures?"

Student: "Because at high temperatures the electrons [*of the semiconductor*] that were well bound to atoms, begin to vibrate and come loose when they reach the ionization energy. This means that there are more electrons to form an electrical current." [Italics added]

'Concept of hole'

With respect to the concept of hole, 15% of the students did not respond because nothing was clear to them [Level 1], and 26% responded inadequately [Level 2]. In the mistaken responses, there reappeared the idea of the hole as a sort of 'holster' or 'housing' for the electron:

Teacher: "What is a hole in a semiconductor?"

Student: "It is where the electron was; really there is nothing, it is like its cavity."

In the responses of Level 3, scored by 28% of the students, the most outstanding finding was that some of them could explain the characteristics of a hole, but could not really accept its existence as a consequence of the model of a semiconductor that was being used:

Teacher: "What is a hole in a semiconductor?"

Student: "The hole is a positive charge, but that is an invention of ours. In reality it does not exist. Well, it exists because there is a hole, but… It is difficult to understand."

Conceptions regarded as appropriate [Level 4] about the properties of holes were expressed by 31% of the students, with arguments similar to the following:

Teacher: "What is a hole in a semiconductor?"

Student: "It is the charge… Well, a positive charge is attributed to it."

Teacher: "Does a hole move?"

Student: "Yes."

Teacher: "How does it move?"

Student: "For example, we have here [indicating a point on the table with his finger] a free space, a hole, and here an electron, and this free electron goes into the hole, we can say then that the free electron has moved or that the hole has moved [indicating with his finger the path of the hole in the opposite direction to what he had indicated for the free electron]."

Teacher: "Is a hole the same as a proton?"

Student: "No. The proton does have a true positive electrical charge. The hole is attributed one, but it does not really have a real charge."

'Generation and recombination of electron-hole pairs'

When the students were asked about the processes of generation and recombination of electron-hole pairs, 17% did not know what to respond [Level 1], and 28% did so incorrectly [Level 2]. The most notable obstacle at Level 2 was again to see the recombination process as an electrostatic interaction between an electron and a hole [Level 2]:

Teacher: "Do the holes have electrical charge?"

Student: "Yes. The holes… they have the same charge as the electrons, but positive, because… the electron occupies the site of the hole, then they are attracted. Charges of different sign attract each other and for that reason they are bound."

Responses in the correct line were given by 28% of the students although with some inaccuracies [Level 3], and by 27% appropriately [Level 4]. An example of Level 4 is the following fragment:

Teacher: "What does the process of generation of an electron-hole pair consist of?"

Student: "In the generation of an electron-hole pair in a semiconductor, em… um… when we apply to a

semiconductor the ionization energy, em… increasing the temperature, then we cause the electrons to vibrate, and that process of generating a hole with the free electron is called generation."

Teacher: "And why does one say pair?"

Student: "It always has to be like that because when the electron becomes free, we also create a hole. One thing goes together with the other."

'Doping a semiconductor'

With respect to the doping process, 15% of the students interviewed said they could not remember anything about it [Level 1], and 20% gave mistaken arguments [Level 2]. In this latter group, there was again the idea that doping consists of introducing electrons into the semiconductor:

Teacher: "What does doping a semiconductor consist of? … What is it done for?"

Student: "It is… when impurities are incorporated into an intrinsic semiconductor, in other words, it is no longer pure."

Teacher: "And what are those impurities"

Student: "Those impurities… those impurities… well, they are electrons of other atoms."

There was also confirmation of the mistaken conception that the purpose of doping is to electrify the semiconductor [rupture of its neutral electrical state]:

Teacher: "What does doping a semiconductor consist of?"

Student: "Well… well, impurities are introduced into an intrinsic semiconductor."

Teacher: "And these impurities —what are they?"

Student: "They are atoms that have three or five electrons in their last shell."

Teacher: "What is the purpose of doping a semiconductor?"

Student: "Well, to charge it electrically."

For the higher response levels, 25% of the interviewees scored Level 3, and 40% Level 4. An example of an appropriate explanation [Level 4] was:

Teacher: "What does doping a semiconductor consist of?… What is it done for?"

Student: "Well… in an intrinsic semiconducting material you have the same number of electrons and of holes, and as you can not obtain more holes than electrons, because otherwise what you are doing is charging it [*electrically*], and you want it neutral but with a different number of electrons than of holes. Then what has to be done is to dope it, to introduce impurities into it, which are elements that have three or five valence electrons." [Italics added]

Teacher: "What type of impurities have to be introduced into a pure (intrinsic) semiconductor to obtain a p-type extrinsic semiconductor?"

Student: "Well, those that have three valence electrons like boron. Because… the covalent bond is made with… see, you have the germanium atom, that has four valence electrons, and you have to unite it with four atoms of germanium for it to share its 4 valence electrons, two by two, and altogether it has eight. But if you put in one with three valence electrons, it only has three electrons to share. As there has to be one electron in each pair of a bond, then in one of the four bonds there will be one missing, and that is the vacancy [*hole*]…" [Italics added]

The results of the interviews confirmed what had been observed from the analysis of the test data relative to the concepts and phenomena that represented the greatest obstacles or difficulties for the students.

(c) Efficacy of the students' self-regulation of learning

We used the students' notebooks to evaluate their progress and learning difficulties as part of their self-regulation process. The assessments and reflections that they had written allowed us to make a qualitative classification of the levels of learning they had attained in the activities of the sequence [a total of 20 activities], and to identify their most significant learning obstacles. The classification levels were:

- Level I: The student still does not understand the activity after the whole-class session.
- Level II: The student corrects his or her initial errors and states that the activity was understood after the whole-class session.
- Level III: The student understands the content of the activity well from the start and needs no correction.

In assigning the learning levels, we also followed the inter-judges agreement procedure. Nevertheless, the

researchers did not have to deduce these levels, since they were self-estimated by the student him or herself, and indicated explicitly following the indicated protocol. Therefore, the percentage of agreement was practically 100%.

Table 6 lists the frequencies of the students' self-estimated levels of learning in each one of the proposal's activities. In all the activities, the number of students who ended by understanding the content [Level II or III] was majority. Also noteworthy was the large percentage of students who needed the whole-class session to understand that content [Level II], reflecting the importance of the discussions and whole-class sessions as essential elements in the students' self-regulation of their learning. The following are some fragments of the commentaries and reflections in the students' notebooks:

Level I: "[…] In class, speaking about this activity, there were times when I have not been able to give an opinion, since I did not know what was being talked about, and I was lost. […] The truth is that I still do not understand the activity well, although I hope that doing the next ones I can manage to understand it, because that has happened to me with other activities." [Student evaluates her learning in the activity A.9.]

Level II: "This activity has been hard for me to understand because I did not know the reason behind it; I supposed that it was because of the sign of the charge. My hypothesis was more or less OK, like that of Laura. My teacher asked me to explain my theory aloud […]. Now that we have finished the whole-class session, I understand it fine." [Student evaluates his learning in the activity A.12.]

Level III: "I did not found any difficulty in this activity, since we studied it recently and I believe that I have assimilated OK the concepts of atom and the particles that make it up. I have observed that during the class, doing this activity, nobody or almost nobody asked anything about it […]." [Student evaluates her learning in the activity A.2.]

We would also emphasize the coherence that we found between the difficulties that the students themselves said they had had during the teaching-learning process, and their levels of knowledge as recorded by the researchers at the end of that process. We observed that the activities in which the students stated they had found the greatest obstacles and difficulties in understanding were those that dealt with the aspects of the subject that presented the lowest levels of knowledge in the test and the interviews. In particular, these activities were those referring to the behaviour of a semiconductor with temperature [A.7, A.8, A.9], to the concept of hole [A.11], and to the electrical state of a doped semiconductor [A.18]. These activities were those with the highest percentage of Level I learning, i.e., those that presented the greatest learning obstacles for the students in the sense that the greatest number of them stated that they had not understood the content even after the whole-class session.

This shows the utility of self-regulation processes for triangulating the evaluation of the students' learning, especially in classroom research situations such as the present case.

Table 6. Frequency of the students' self-estimated levels of learning for each of the activities as part of the self-regulation process.

Content studied	Activities	Self-estimated level of learning		
		Level I (%)	Level II (%)	Level III (%)
Importance of semiconductors in electronics	A.1	14.3	33.3	52.4
Concept of semiconductor	A.2	13.8	31.7	50.0
	A.3	13.3	21.7	65.0
Internal structure of an intrinsic semiconductor	A.4	11.7	38.3	50.0
	A.5	10.0	33.3	56.7
Electrical behaviour of semiconductors	A.6	15.0	33.3	51.7
Generation and	A.7	40.0	41.7	18.3

recombination of electron-hole pairs	A.8	35.0	45.5	20.0
	A.9	38.3	48.3	13.3
Charge carriers of a semiconductor	A.10	13.3	56.7	30.0
	A.11	43.3	45.5	11.7
	A.12	15.0	43.3	41.7
	A.13	15.0	16.7	68.3
	A.14	26.7	38.3	35.0
Extrinsic semiconductors	A.15	20.0	35.0	45.0
Impurities and the doping process	A.16	18.3	61.7	20.0
	A.17	10.0	41.7	48.3
Behaviour of p-type and n-type semiconductors	A.18	35.0	36.7	28.3
	A.19	18.3	56.7	25.0
	A.20	16.7	31.7	51.7

The students' overall valuation of the teaching-learning process

Finally, we shall describe how the students who were interviewed assessed the semiconductor physics teaching-learning process. In general, we can say that they were satisfied with the content and with the method. Thus, asked about the design and the practical implementation of the teaching sequence, they emphasized their satisfaction and motivation during the study of the subject, basically because of how the content was presented in class:

> Student A: "I liked the subject of semiconductors more than other subjects, and I believe that it was due to how it was studied. If the subject were studied through textbooks, I believe that it would be the same as with the other subjects."

> Student B: "For me, it has been easier this about semiconductors than, for example, that about formulating chemical compounds. But I believe that it was because of the form in which we studied it. The content is easier to take, and that has a lot of influence for understanding better."

The students also showed the interest that the study of semiconductor physics as part of their scientific education had aroused:

> Student C: "[…] as we were advancing in the subject, the interesting things about semiconductors were coming out, and so I finally ended up liking it a lot."

Also, the students valued positively the group work aimed at fostering cooperative learning, the whole-class sessions for the activities, and the practices of self-regulation of learning:

> Student D: "[…] team work has been encouraging, because, if you did not understand something, you got together with your companion: 'Let's see, can you help me in this activity?' I saw that people were really keen to ask their companions about their doubts. We all have worked well together."

> Student E: "[…] above all I liked the whole-class sessions, that once we had done the activities we put the ideas together, discussed them… and with that you learn a lot."

> Student F: "What I did [*during the whole-class sessions*] was to write down what people said, to write down what I did not understand very well; if I understood it, if it had been difficult for me or not; what I had found hard, etc. Perhaps I did not do all this in all the activities, but in almost all." [Italics added]

But the learning process was no easy task for the students. Throughout the teaching sequence, the students had to work in a team, and to develop such procedures as formulating questions, posing hypotheses,

selecting, organizing, and processing information, communicating conclusions, etc. Also —as we noted above— they had to reflect continually on their learning, and recognize and deal with their errors, difficulties, and progress [self-regulation processes]. This all required a major effort on the part of the students as is seen in the following statements:

> Student G: "What cost the most was that whenever you did an activity, you had to write a commentary on what you had learned, and sometimes I did not know clearly what commentary to write."

> Student B: "The way in which we worked on the subject forced me to pay more attention in class, since I had to write up how I had learned and what was said while we were doing the whole-class sessions of the activities."

> Student H: "[…] what required most effort from me… since, sometimes, the things were difficult and you had to be looking for information all the time, and asking for help from companions, continuously, to solve the activities."

Also, the students stated that they had found difficulties in understanding some of the concepts and phenomena studied, as had been shown by the other evaluation instruments. The following statements are examples:

> Student I: "There are aspects that I never managed to understand well, like, for example, that of the behaviour of semiconductors at high temperatures. Also, that about doping."

> Student H: "[…] what cost me most to understand was the concept of hole… well, I still do not get it clearly."

> Student J: "What cost me most to understand is that of the hole, and the last part, about doping […]."

Conclusions and teaching implications

The pilot study presented here has analyzed the effectiveness of a teaching sequence oriented to introducing notions of semiconductor physics in SE. One can conclude from the results that it is feasible to give a first introduction to the topic in the sense that the students were able to familiarize themselves with its basic concepts. Nevertheless, the learning obstacles detected suggest that new studies should be done —as it will be discussed below— that go deeper into the subject, and contribute to improving its teaching at this educational level.

With respect to the teaching-learning process that was applied, the results indicated that the strategies followed to implement the sequence contributed to the students learning to construct their own knowledge. This was achieved because a high priority was given to encouraging a good working and communication climate in the classroom, both among the students and with the teacher. Similarly, the students were encouraged to evaluate and monitor the progress and difficulties of their own learning [self-regulation]. It was found that this practice, which was highly valued by the students, led to cooperative learning and the whole-class sessions for each of the activities taking on especial importance. This all helped the students to learn to learn by being in permanent interaction with their classmates. In addition, it fostered the development of communication skills in the students. Nonetheless, it is necessary to say that accustoming the students to this form of learning science required a time of prior training.

The results also indicated that in general the students developed positive attitudes towards semiconductor physics and its learning. These attitudes, seen in the high level of stimulus of the students during the learning process, were encouraged fundamentally by the way the content was dealt with in class. In particular, the students positively valued: (a) the group work and the whole-class sessions as essential parts of the process of self-regulation, and (b) the way the content was adapted to their level, most of it being —according to the students themselves— eventually comprehensible.

With respect to the learning of concepts, it was found that around two-thirds of the students acquired ideas that were either appropriate [Level 4] or close to appropriate [Level 3] with respect to: (1) the recognition of a semiconductor from the electronic configuration of its elements, (2) the process of generation and recombination of electron-hole pairs, (3) the generation of free electrons by doping with donor impurities, and (4) the balance of charge carriers in an extrinsic semiconductor. The main obstacles and most frequent learning difficulties were related, in this order, to: (i) the electrical state of a doped semiconductor, (ii) the behaviour of semiconductors with temperature, (iii) obtaining a p-type extrinsic semiconductor, and (iv) the concept of hole, although this last difficulty was also the cause of part of the previous obstacles, as we shall

see below.

It is possible that the simplifications involved in the 'didactic transposition' of the topic to the SE level contributed in some way to the appearance of some of the learning obstacles detected. It has to be borne in mind that the topic is usually studied —in post-obligatory education— from a quantum physics perspective, whereas we have approached from a classical standpoint. We think, however, that, at a basic level of education, a simplified classical model of a semiconductor such as that we used offers more benefits than drawbacks in allowing a first introduction to the subject.

One might also wonder whether the level of abstraction of some of the concepts were not beyond the usual capacity of a 14–15 year old, and that therefore it would perhaps be advisable to put off their introduction until a higher educational level. Nevertheless, since we are at just the first steps of the project, we think it is still too early to make decisions of this type, and that it is preferable to first go more deeply into the subject with new research. At this point, we have already been able to make a first evaluation of the effectiveness of our teaching sequence.

Following Martinand, in order to improve the effectiveness of the sequence it was necessary to determine the obstacles that the students encounter in learning the topic. This information allowed us to reformulate some of the initial learning objectives in order to anticipate and try to avoid those obstacles in future implementations —since we can no longer teach the topic again to the same students. In the following, we summarize the main learning obstacles detected, and indicate the initial objectives which were reformulated for subsequent actions.

Behaviour of semiconductors with temperature

The first obstacle that the students faced was that many tended to think that the intermediate electrical behaviour of semiconductors at room temperature is because these materials simultaneously have the properties of conductors and of insulators [half conducting and half insulating]. To obviate this, we will need previously to convince the students that the electrical behaviour of semiconductors —as of all materials— depends on their structure and chemical composition, and that these properties can change as the temperature changes, giving rise to one or another electrical behaviour according to the particular value of the temperature. In this sense, we think that it is fundamental that, before studying the sequence, the students acquire the appropriate basic ideas about the covalent bond in solids, ionization energy, and the kinetic theory applied to solids —as we already advanced at the beginning. In addition, this leads us to reformulate learning Objective 2.1 [cf. Table 1] as follows:

2.1. To understand that:
− The electrical behaviour of a material [conductor, insulator, or semiconductor] depends on its structure and chemical composition.
− Semiconductors [covalent solids] can vary in electrical behaviour with temperature in accordance with kinetic theory, but that behaviour is specific [insulator, conductor, or intermediate between the two] for each value of the temperature.

Another obstacle detected was in understanding the cause-effect relationship between temperature and the resistivity of a semiconductor. Some students confused [inverted] this relationship thinking that changes of temperature in this material are determined by changes in resistivity. We think that this will be avoided if the students come to the study of semiconductors with the prior conceptual baggage that we described above with respect to the previous obstacle. Indeed, the relationship between resistivity and temperature demands that the students are first able to relate the number of charge carriers [free electrons] in the material to the temperature at which it finds itself [kinetic theory]. I.e., as the semiconductor's temperature rises, the bonds begin to break [on receiving the corresponding ionization energy] and there will be more charge carriers available to form part of an electrical current. Then, since resistivity is a measure of the difficulty that materials have in conducting electricity, it can be concluded that as the semiconductor's temperature increases this difficulty [resistivity] gets less. In sum, the key ideas are: (a) 'If the temperature of a semiconductor increases, its resistivity decreases [not the other way round]'; and (b) 'If the resistivity decreases, the semiconductor's capacity to conduct electricity increases'. We thus reformulated Objective 3.4 as follows:

3.4.a. To understand that electrical resistivity:
− Is a characteristic parameter of materials and independent of their dimensions, which gives an idea of their capacity to

conduct electricity.

− Depends on the internal structure of the material, the temperature at which it finds itself, and the amount of charge carriers that it has, in accordance with kinetic theory.

3.4.b. To understand that:

− Intrinsic semiconductors become good conductors of electricity at high temperatures —even better than typical conductors— because the bonds of their covalent structure break and release valence electrons [when they attain their ionization energy] which can carry electrical currents [low electrical resistivity].

The concept of hole and the processes of generation and recombination

With respect to the concept of hole, we found the following most significant learning obstacles:

• The assignment of corpuscular properties to holes [vacancies in the crystal lattice] is poorly assimilated by the students.
• The students do not accept the idea that holes are positive charge carriers in a semiconductor.
• The students think that, in the recombination process, a hole is a sort of permanent 'holster' for an electron, which acquires the charge of the electron that comes to 'occupy' it.
• The students take the holes into account in deciding whether or not a semiconductor is electrically neutral as if they were [real] physical charges.
• The students see recombination as an electrostatic attraction of charges of opposite signs, in particular, between holes and free electrons.

Perhaps the concept of hole is the most abstract of those dealt with in the teaching sequence. We found that games and simulations allow the students to understand the generation and recombination of electron-hole pairs in a semiconductor. And also that those holes, by continual processes of generation and recombination, behave as if they were moving through the material in the opposite direction to the free electrons. The difficulty arises when that 'vacancy' is in addition assigned a positive electrical charge. We think that the first thing to do is to try to convince the students of the need to 'resort' to the idea of hole to explain the electrical behaviour of semiconductors. This can be achieved by using some simple analogy using balls and cups, the idea being to demonstrate to the student that, as a first approximation, it is sometimes easier to explain the movement of electrons in a semiconductor by following the movement of the holes. And as the holes seem to move in the opposite direction to the electrons, it is useful to regard them as positive charge carriers because, if a voltage is applied to the semiconductor, the free electrons will move from the negative pole to the positive [as the students already know], while the holes seem to move from the positive pole to the negative. Nonetheless, it is advisable to anticipate by warning the students that, being a fictitious charge, it must not be confused with the charge of the proton, that indeed is real and does not move through the material as it is inside the atomic nucleus. In this way, it would be possible to also avoid the last of the obstacles indicated above.

Also with respect to this last obstacle, for the students to manage to understand why recombination takes place, they first should analyze what happens to the energy of an 'object' after it undergoes numerous collisions in its path. We believe that in this way they will be able to see that the free electrons progressively lose part of their energy in the multitude of collisions with atoms of the lattice, and end up by 'falling' into the holes created by other liberated electrons.

We think that in introducing the concept of hole it will be necessary to spend some time —*a priori* we do not know how much— in getting the students to see that decisions such as that of assigning corpuscular properties to the holes are frequent in science, especially when one is constructing models to try to explain the microscopic phenomena of matter ['those that we can not observe by eye']. I.e., in order to understand the 'unknown', one usually assigns it properties of other known objects. One can get the students to remember that in previous years they have used analogical-type models when they approached the study of the matter, with such expressions as: "atoms are 'little balls'" in the atomic model of Dalton; "the nucleus is like the Sun and the electrons are like planets" in the atomic model of Rutherford; and "atoms are the 'bricks' that constitute matter". We therefore believe that the assimilation of the concept of hole can be reinforced by using various analogies —in addition to those explicitly proposed in the teaching sequence— in the line suggested by Oliva et al. (2003, 2007).

In light of the foregoing, we decided to reformulate Objectives 3.6, 3.8, and 3.9 as follows:

3.6. To understand that:

− Electrostatic interactions only occur between real electrical charges.
− In the process of recombination of electron-hole pairs, by losing part of their energy the free electrons return to being bound to the semiconductor's crystal lattice, occupying a hole [vacancy] left by another electron.

3.8–3.9. To understand that:

− The hole is a 'particle' defined as a consequence of the model that is used to study a semiconductor, and that it therefore only has an 'existence' in these materials.
− The concept of hole is defined in order to facilitate the study of electrical conduction in semiconductors. In other words, sometimes it is easier to follow the movement of the holes [vacancies left by liberated electrons] than of the free electrons themselves.
− The charge of the holes is manifest in their [apparent] movement: holes are positive charge carriers in a semiconductor.
− The positive charge assigned to the holes is fictitious. Therefore, it must be distinguished from the real positive charge of protons.

Extrinsic semiconductors: doping a semiconductor with impurities

With respect to extrinsic semiconductors, we found various learning obstacles, some of which arose from the inadequate understanding of the concept of hole. These obstacles were the following:

- The students see holes as 'defects' in the semiconductor's crystal lattice, and therefore that donor impurities are introduced in order to correct these defects.
- The students think that a donor impurity is an electron, and an acceptor impurity, a hole.
- The students identify doping with a process equivalent to that of generating electron-hole pairs, i.e., a process that consists of raising the semiconductor's temperature in order to release electrons and thus lower the resistivity.
- The students think that an extrinsic semiconductor ceases to be electrically neutral because it no longer has the same number of free electrons as holes. They therefore think that p-type semiconductors are charged positively, and n-type, negatively. In sum, again it is a case of their not distinguishing holes from protons.

To avoid these obstacles in subsequent implementations of the teaching sequence, as well as what was said above with respect to the concept of hole, we will try to stress that the impurities with which semiconductors are doped are atoms, and therefore electrically neutral and incapable of altering the electrical state of the semiconductor. On the basis of what the students already know, we think that this can be achieved by including some activity where the students are asked to make a count of the protons and electrons in a portion of some [homogeneous] material in which there exists a certain quantity of two different types of atoms [as is the case in an extrinsic semiconductor], and determine whether or not it is electrically charged.

Consequently, we reformulated Objectives 4.1, 4.2, and 4.3 as follows:

4.1 To understand that:

− Doping is a process that allows a semiconductor's electrical conductivity to be improved without increasing its temperature.

− Doping consists of inserting impurities into the semiconductor so as to generate different numbers of free electrons and holes in it.

4.2.a. To understand that:

− A material's electrical state is determined by the difference in the number of electrons and protons that it has.

4.2.b. To distinguish between:

− Real charges [electrons and protons] and charge carriers [free electrons and holes] in a semiconductor.

4.2.c. To understand that:

− The impurities with which a semiconductor is doped are atoms, and therefore electrically neutral, with sizes that are similar to that of the semiconductor atoms [Si or Ge] so as not to significantly alter the crystal structure.

- Extrinsic semiconductors are electrically neutral because they are obtained from [neutral] intrinsic semiconductors doped with impurities that are also neutral.

4.3 To understand that:

- The impurities are atoms: donors [pentavalent atoms] contribute free electrons to the semiconductor, and acceptors [trivalent atoms] contribute holes to the semiconductor.

Evidently, the above discussion and reformulation of the learning objectives implies revising a part of the initial activities of the teaching sequence. Nevertheless, for reasons of space we will not deal with that here, but instead leave it for a future work in which we shall also analyze the sequence's effectiveness with new students.

Finally, we would say that as we are unaware of other studies that have approached the present topic, we have been unable to make comparisons to validate our results. We also realize that the present results are not generalizable to other educational contexts [they lack external validity], among other reasons, because the study was conducted in a specific natural context of educational practice [the sample of students was chosen for convenience]. Nonetheless, we believe that the variety of research instruments used [test, personal interviews, and student notebooks] and the validation and reliability analyses performed lend sufficient rigour to the study. In this sense, we think that it constitutes an important point of reference from which to undertake new studies —both in educational contexts similar to ours and in different contexts— which would look deeper into the aspects dealt with here, and consequently shed further light on the issue. We hope therefore that there will arise new lines of research related to the topic, because at present there are still very few in science teaching.

Footnotes

i. There are other differences, such as that free electrons can move roughly twice as fast as holes. Nevertheless, because of the complexity that would be involved in studying such aspects, we choose not to deal with them at the SE level.

ii. This is a simplification to represent the collective electrical contribution of the electrons of the valence band which is almost full.

iii. In general, by doping semiconductors the designers of electronic devices are able to control electrical conduction in these materials, and thus achieve new and better electronic applications. In this introduction to extrinsic semiconductors at the SE level, however, we think that it is sufficient for the students to understand that doping allows one to obtain a semiconductor that conducts electricity well at room temperature, which is not the case in an intrinsic semiconductor.

iv. In practice, n-type semiconductors are more interesting since their majority charge carriers are free electrons which have a greater mobility than holes [the majority charge carriers in p-type semiconductors]. Nonetheless, we do not deal with this in our teaching sequence since the explanation would be complicated for SE students.

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Appendix: Evaluation test on basic notions of semiconductor physics

1. The atoms of certain homogeneous material have 4 valence electrons. At room temperature:

    a) It is a better conductor than metals.
    b) It is a better insulator than non-metals.
    c) It is a better conductor than non-metals and worse conductor than metals.
    d) It is a worse conductor than non-metals and worse insulator than metals.

Justification of the response:

2. At high temperatures, an intrinsic semiconductor:

    a) Becomes a good conductor of electricity.
    b) Behaves the same as a conductor, i.e., a bad conductor of electricity.

     c) Behaves as an insulator of electricity.

Justification of the response:

3. The holes in a semiconductor behave as:

     a) Electrically neutral particles.
     b) Negative electrical charges.
     c) Positive electrical charges.
     d) Protons.

Justification of the response:

4. In the generation process:

     a) There appears an electron-hole pair in the semiconductor.
     b) There appears a hole and a free electron disappears.
     c) There appear more free electrons than holes.

Justification of the response:

5. Explain how a free electron is generated in a semiconductor by doping it with a donor impurity.

6. How is a p-type extrinsic semiconductor obtained?

7. In an extrinsic n-type semiconductor, which are the majority carriers? Why?

8. If we put two donor impurities into a pure [intrinsic] semiconductor, will it still be electrically neutral? Give reasons for your answer.