University of Palermo – Physics Education Research Group

Un percorso di apprendimento inquiry-driven sulle proprietà del trasporto elettronico nei semiconduttori.

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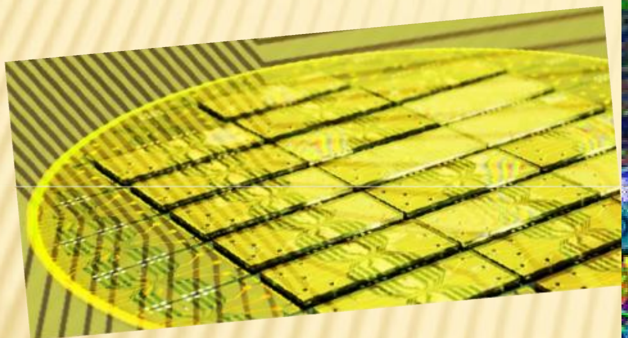
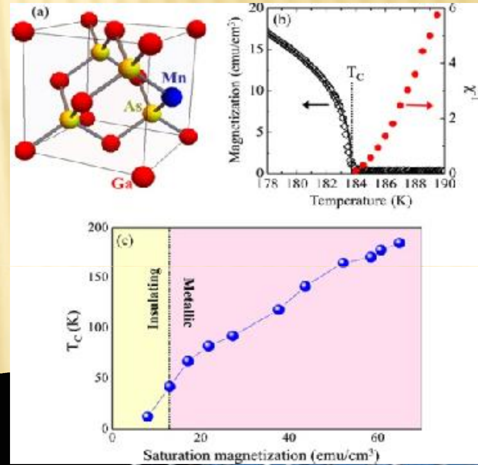
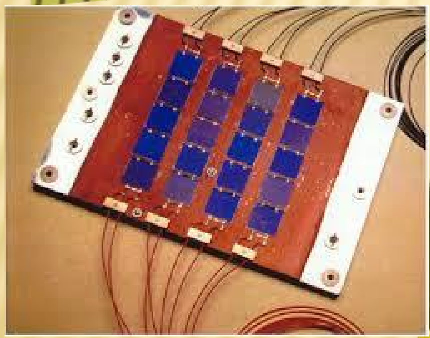
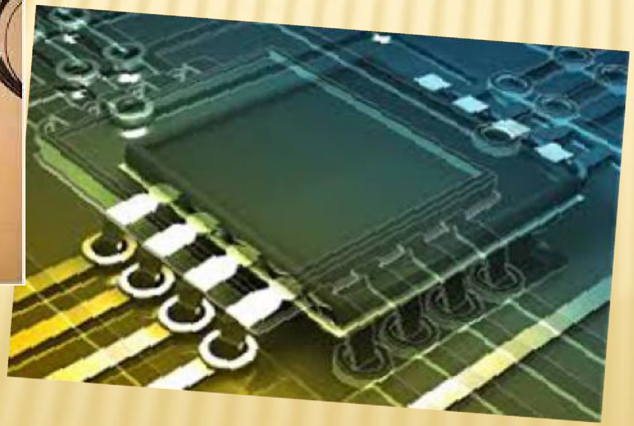
Motivation for this study

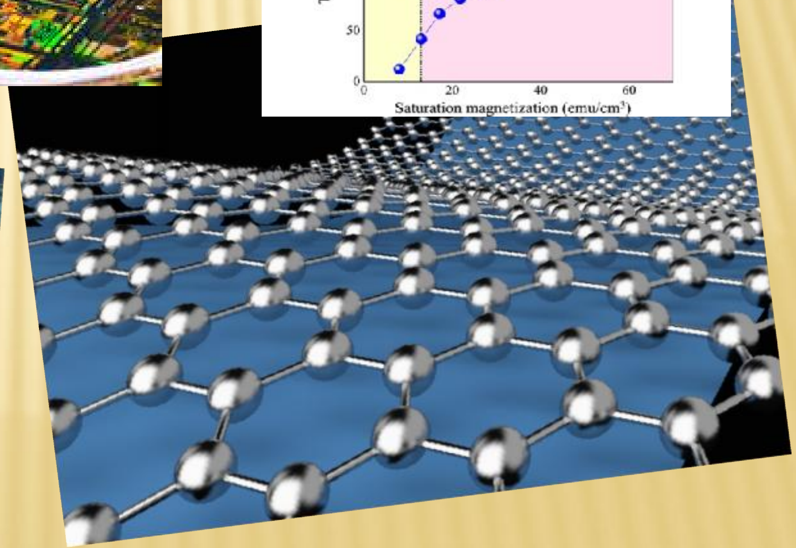
The knowledge of semiconductor transport properties is a fundamental instrument for any physicist or engineer involved in semiconductor technology.











Actual state of art in Semiconductor Instruction:

- A traditional lecture-based instruction of solid state physics provides the students with a theoretical background regarding the band structure, the concept of effective mass and the basic phonon-induced scattering mechanisms.

What we need:

- An effective and efficient engineering instruction, should be able to train the students towards a full comprehension of the fundamental concepts of semiconductor science and, at the same time, develope and strengthen reasoning skills and transversal abilities, enable graduates to immediately engage in engineering practice and related technologies.
- Graduate engineers should be able to demonstrate both specialist-discipline knowledge, ability to solve practical engineering problems, and design skills based on innovative thinking.

At university level, Solid State Physics education is mostly based on courses which are aimed to introduce theoretical concepts.

This approach cannot be successful:

1. People experience the world around them everyday; mental constructions cannot exist without experience; scientists develop physics theories to cope their need of explaining the observed phenomena;
2. Students seldom fully understand a theory, even if currently accepted, if it is left far from a direct experimentation.

Many reports propose a new vision of active construction of meaningful knowledge, suggesting to switch from a passive lecture-style teaching to a more active and student-centred teaching strategy.

In this context, inquiry-based education represents the natural framework to develop opportunities of learning science concepts in terms of an active construction of meaningful knowledge and stimulate high levels of critical thinking skills.

INQUIRY BASED SCIENCE EDUCATION

"*Science learning is an active process*" in which students gain skills as critical observing, inferring and experimenting.

Inquiry is central to science learning.

Dictionary meaning of Inquiry: seeking knowledge, information, or truth through a questioning activity.

Inquiry based learning is a way of converting information into *useful* knowledge.

Inquiry is a form of active learning: students are engaged in various integrated activities of identifying questions, collecting data and evidences in a laboratory or real life environment, building descriptions and explanation models, communicating and sharing their findings.

The method

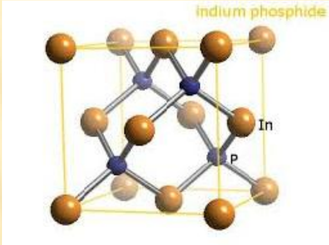
The setup of real experiments on semiconductors is not easily available in most university laboratory for large numbers of students:

numerical simulation, being considered a practice in between theory and experiment, could represent a valid alternative.

The Monte Carlo method allows to powerfully simulate the charge transport in semiconductors, beyond the quasi-equilibrium approximations. This technique represents a space-time continuous solution of the transport equations, giving a detailed description of the particle motion in a semiconductor:

- It is suitable for studying both the steady state and the dynamic characteristic of a device.
- It accounts for the main details of band structure, scattering processes and heating effects, specific device design and material parameters.

The challenge of an inquiry experience elucidating the electron transport in semiconductor crystals of InP at University of Palermo



Participants

Students: A sample of 10 students in electronic engineering at the Laboratory of Condensed Matter Physics of the Department of Physics and Chemistry, University of Palermo, Italy, participated to this study (8 males and 2 females).

The students were selected among those who attended more than 80% of the traditional course on condensed matter physics.

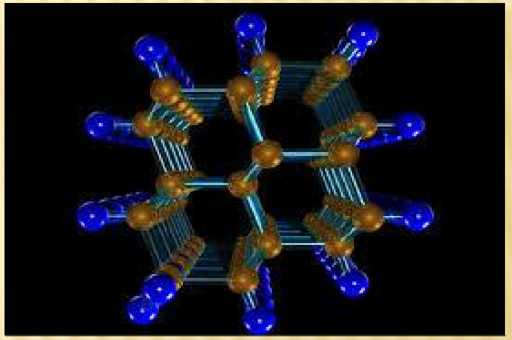
Instructors: Students scientist-like activities were supported by two teachers having more than 15 years of expertise in the field of scientific research and on teaching physics at both high-school and University level courses.

The activity description

The task: explore the electron dynamics in a semiconductor bulk of InP by means of MC simulations, addressing the role of:

- ✓ effective mass,
- ✓ intervalley and intravalley scattering,
- ✓ impurities
- ✓ lattice temperature

on carrier dynamics.



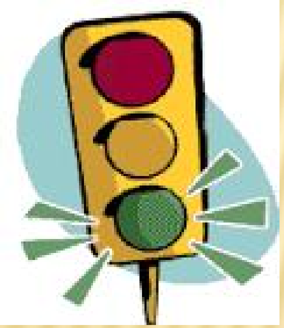
The students, working in groups, had to design their own procedure of exploration, as expected in a traditional guided inquiry.

Although our students had first received a traditional lecture-based instruction on semiconductor physics and attended a seminar on the use of MC procedures, when involved in the learning path, they experienced several difficulties on planning and carrying out a meaningful sequence of simulative experiments, many times coming to a standstill.

The need for an elicited inquiry…

At this stage, the instructors actively participated to the students' debate on the physics governing the charge dynamics, never providing exhaustive explanations to the students, but giving comments and hints, sometimes expressly incorrect, but effective to stimulate students' reasoning and activating a proficient scientific inquiry.

The active participation of the instructors to the discussion as peers activated student scientific inquiry through the onset of an effective questioning:



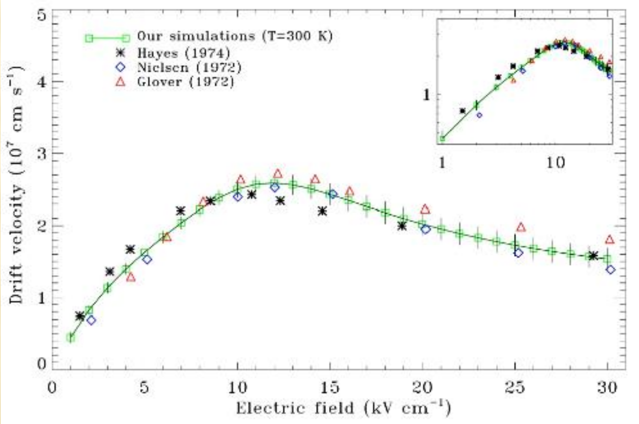
→ after the initial model validation, the stimulated inquiry learning path was articulated in three successive phases; each one started from a reasoned question and included a set of simulative experiments whose results are explicative at some level of understanding and, at the same time, boosting the learners' thinking with further questions to be addressed by a deeper scientific inquiry.

Model validation

Before starting to use a model developed by others, our students tested its validity, by comparing the computational outcomes with experimental data reported in literature.

In this phase:

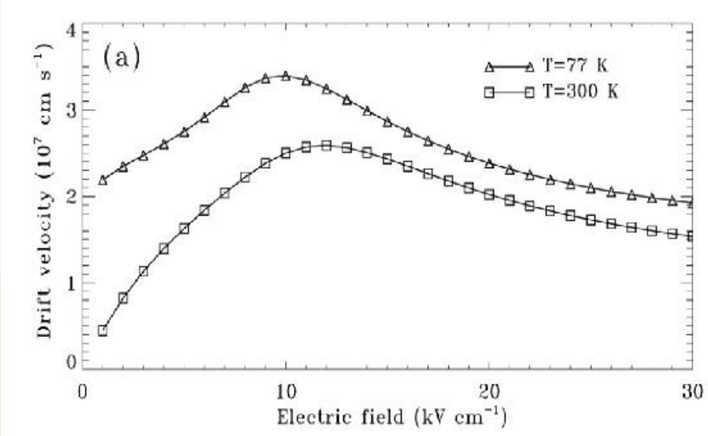
the students carefully checked the conditions under which the experiments were carried out (lattice temperature, carrier density, etc), in order to set the correct parameters in the code and focused their attention on the capacity of their simulated data to closely reproduce the corresponding experimental values, leaving the effective understanding of the physics beyond their findings to a subsequent explanatory phase.



the instructors drove students' inquiry towards the exploration of those model parameters which can be opportunely tuned to achieve their goal.

Question 1: Which physical quantities affect the velocity-field characteristic?

The students found the presence of a nonlinear velocity-field characteristic, with an initial increasing phase of the electron drift velocity, followed by a maximum (at ~10 kV/cm) and a subsequent region, characterized by a decreasing velocity for higher values of the electric field.



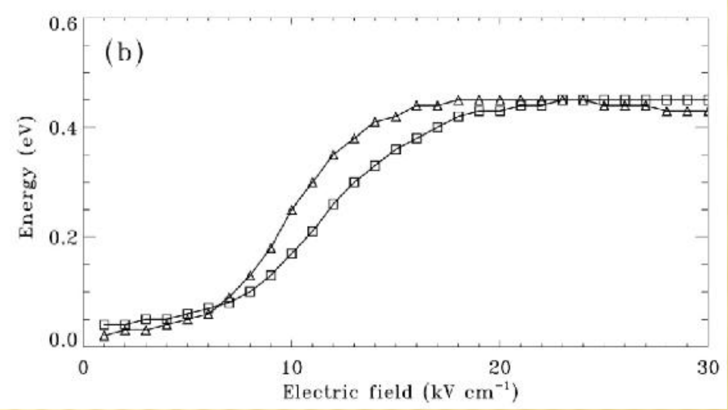
In this phase:

This result represented a surprise for students, who probably expected to find the well known ohmic behaviour. In effect, in the low field region the velocity-field dependence resembles the familiar Ohm's law, while a significant deviation from it is clearly evident at stronger electric fields.

The instructors stimulated the students to inquiry about this phenomenon, in order to address the physical reason beneath the observed decrement of the electron drift velocity.

Question 1: Which physical quantities affect the velocity-field characteristic?

In the range 1-8 kV/cm, the mean energy increases slowly up to ~0.1 eV. Higher driving fields cause a rapid enhancement of the electron energy up to a saturation regime at about 0.4 eV.



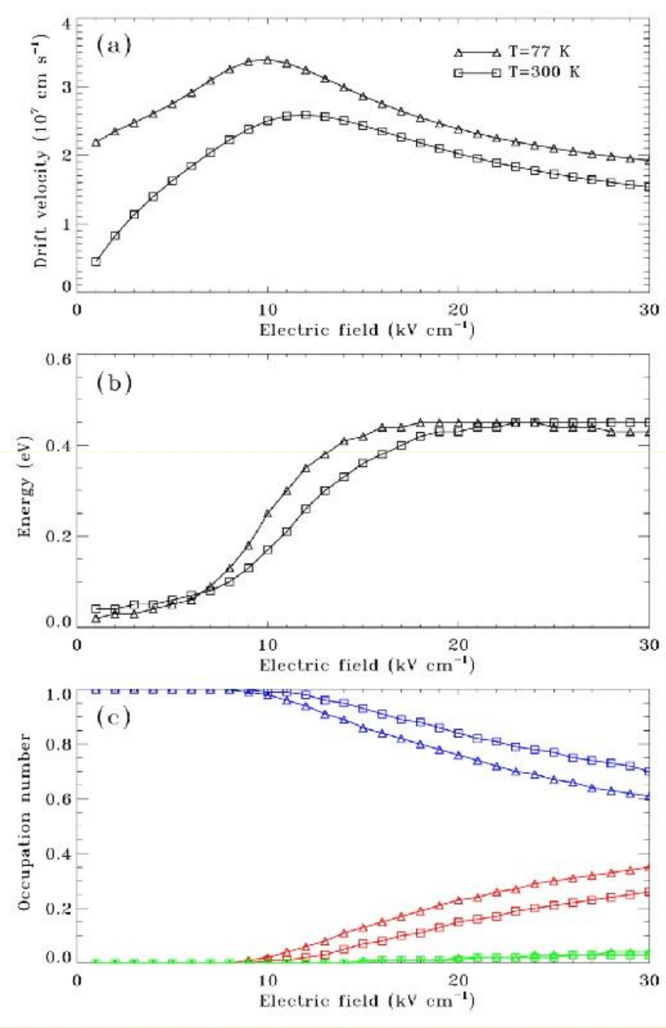
At this stage:

This result was twofold surprising for the students who firstly expected that the mean energy always follows the electron velocity characteristic and consequently drop as the mean velocity does, and secondly they did not expect a saturation of the energy levels, but eventually an increase for higher driving fields.

A discussion was stimulated by the instructors on how this phenomenon could be physically explained and, in particular, they questioned: “What really happen to the electron ensemble at higher electric fields? ”

Question 1: Which physical quantities affect the velocity-field characteristic?

The application of an electric field causes the electrons to increase their energy until they have the possibility to transfer from the Γ-valley to the higher energy valleys, where the effective mass is greater (heavy electrons).



At this stage:

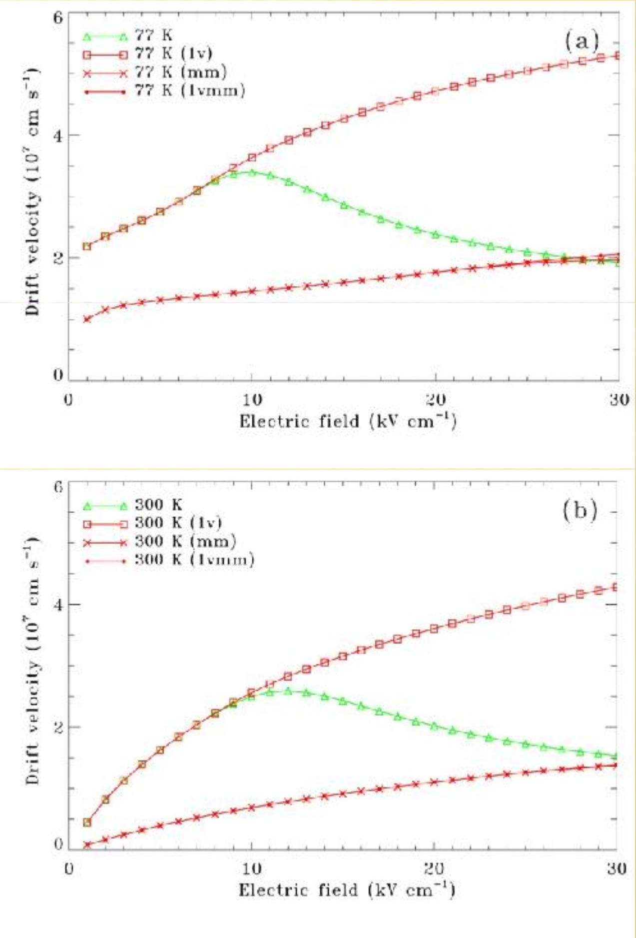
The students noted that electrons start to populate the higher valleys when the electric field amplitude reaches values greater than about 10 kV/cm, the same value characterizing the maximum of the velocity-field characteristic. This finding supported the importance of taking into account the effective mass of charge carriers and the fundamental role played by scattering events, finally responsible for intervalley transitions.

Question 2: Which is the role played by the effective mass?

A reasoned inquiry guided the learners through a deeper exploration of the role played by the effective mass of drifting electrons.

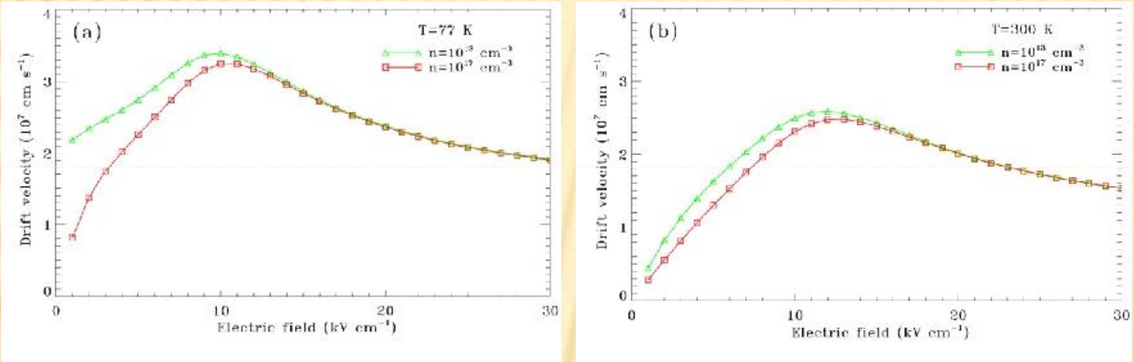
In this phase:

The students carried out different simulations and compared the results obtained by using the three-valley model (green triangles) and those coming from the single-valley (Γ) model (red squares, “1v”), in which the electron transitions to higher energy valleys are inhibited. Moreover, they investigated the effects of considering all electrons having the same mass, but this time equal to the average value among the effective masses for different valleys.



Question 3: *What are the effects due to a change on the impurity density*

To highlight the effect of the interactions between free electrons and ionized impurities, randomly distributed inside the crystal, the instructors stimulated the students to investigate the peculiar characteristic of the electron transport in InP at different values of the doping density.



At both the temperatures, the effect of impurity scattering is relevant only in the low-field region, where a decrease of the mean drift velocity occurs.

Since ionized impurities scattering appear to be relevant mainly at low fields and/or at low temperatures, the students concluded that the impurity scattering rate decreases when the electron energy increases, becoming negligible in the high-field region.

The inquiry-based learning cycle

The cycle of inquiry-based learning, caused by unexpected results, evolving through a series of investigations supporting working hypothesis, was closed back by an explicatory phase where the students were stimulated to share their views and discuss among each other about the convincing evidence.

Table I

Inquiry sequence	Reasoned student questions	Planned simulations	Concepts acquired
Phase I	1) Which physical quantities affect the electron velocity-field characteristic? 2) How the electron energy changes at different values of the driving electric field? 3) What really happen to the electron ensemble at electric fields higher than the Gunn field?	Study of drift velocity, energy and occupation number of electrons in InP bulk for lattice temperature T=77 and 300 K and a driving electric field ranging between 1 and 30 kV cm^{-1}.	Gunn Effect; Role of intervalley transition; Dependence of phonon scattering probability on the temperature.
Phase II	How can we be definitely sure that the observed maximum in the velocity - field characteristic can be ascribed to intervalley transitions?	Study of electron dynamics, forcing all electrons to remain in the Γ-valley, independently of their energy and changing the value of the effective mass.	Effective mass as a measure of the inertial response of the system.
Phase III	What are the effects due to a change on the impurity density?	Study of electron dynamics at different values of the doping density.	Dependence of intravalley transition probabilities on the energy; Screened Coulomb interaction.

Students' reasoned questions, effective in overcoming the standstills, together with the planned simulations and the concepts reinforced by the analysis of the outcomes from the numerical experiments.

Discussion

The relation between our teaching intervention and the student cognitive and affective development was investigated by methods of discourse and behavior analysis, including the study of speech events and gestures.

In order to explore the student learning process from the widest point of view, we collected data both during the initial phase of traditional guided inquiry and after the succeeding inquiry with the intervention of instructors' elicitation.

Also student questionnaires, planning files, logbooks of experiments, final scientific reports have been analyzed.

DISCOURSE ANALYSIS

Distributed cognition treats thinking not as an action that takes place wholly inside an individual's head, but rather as a distributed activity among other people and their language (Winsor, 2001).

Videotaped data were analyzed on the basis of an in-context search for keywords or phrases characterizing specific aspects of the student's behavior.

Speech Events (SE) (Donath et al. 2005)	**Percentage of students showing SE during the simulated experiments on semiconductors**	
	Traditional Guided Inquiry	Elicited Inquiry
1) Diagnosing	30%	60%
2) Critique	40%	70%
3) Explanation of research	40%	80%
4) Awareness of knowledge gained	20%	60%

On average, our elicited inquiry path recorded about 35% of increase in the number of students showing speech events, with respect to a traditional guided inquiry.

DISCOURSE ANALYSIS

Some quotes from students' speech events:

<u>Diagnosing:</u>
"To address the role of scattering events, we could change the temperature in the simulations"

<u>Critique</u>:
"This finding cannot be real, I expect to see a drop in the carrier velocity ..."
"We have to repeat the simulation: the energy saturates ..."

<u>Explanation of Research</u>:
"Yes! It's the effective mass that drives the inertial response of the semiconductor system."
"Ok: scattering with ionized impurities is effective only at low temperatures..."

<u>Awareness of knowledge gained</u>:
"Now I have finally understood the role of intervalley transitions!"
"Yes, I got it: the effective mass determines the electron dynamics!"

Intrinsic Motivation Inventory (IMI)

Information about the student affective development and motivation to learn was achieved by using a questionnaire based on the Intrinsic Motivation Inventory (Ryan, 1982; McAuley et al., 1989; Ryan & Deci, 2000; Vos et al., 2011), with specific items adapted to our study.

To quantify the student satisfaction we use a five-point Likert scale

5: Very much
4: Somewhat
3: Undecided
2: Not really
1: Not at all

The IMI is a multidimensional measure of subject's experience with regards to experimental tasks developed by the Rochester Motivation Research Group.

Intrinsic Motivation Inventory (IMI)

Questions (interest-enjoyment dimension; perceived competence dimension)	Mean student outcomes on a five-point Likert scale	
	Traditional Guided Inquiry	Elicited Inquiry
1) I enjoyed this learning experience.	2.9	4.5
2) I am satisfied with my performance at this experience	2.1	4.4
3) After this learning experience, I feel pretty competent	1.8	3.9
4) I'm pretty skilled on Semiconductor transport	1.8	3.6

The statistical analysis of these four students' answers has shown a greater student appreciation up to 55% of the elicited inquiry environment with respect to the guided one.

This confirms the awareness achieved by the students about the benefits that a specific activation of the inquiry process has had on stimulating their active role into knowledge construction.

Summary and Conclusions

✓ An effective knowledge of scientific concepts is achieved when the student is able to apply those concepts to solve problems never encountered before.

✓ An appropriate training on problem solving has to be based on the development and strengthening of student reasoning skills.

✓Higher levels of thinking abilities can be achieved by “forcing” the students to personally experience the world and struggle for finding solutions to real problems. This can be done by teaching the students to pose scientifically relevant questions, carry out scientific investigations, how to get significant measurements and analyse data, draw explanatory models, check results with further questions, share and discuss findings with peers.

Summary and Conclusions

✓ Teacher's role on providing suitable scaffolding is fundamental. Inquiry-based learning environments with lower teacher guidance may stimulate higher reasoning skills, but sometimes may produce negative feelings due, for example, to run into mistakes or achieve unexpected results (especially in not real-life problems).

Our results show that the process of scientific inquiry in students facing unexpected findings in the study (even following a guided-inquiry based approach) of semiconductor physics (as in theoretical topics not directly observable in lab) may need a specific activation of the questioning process, supporting a valuable reasoned exploration.

The stimulation of the student inquiry process constitutes an efficient teaching approach to effectively engage students into an active learning. This may represent a viable example of integration of a traditional lecture-based teaching approach with effective inquiry-based learning strategies.