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Lab on the Web—Looking at Different Ways of Experiencing Electronic Experiments*

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Students who perform a laboratory exercise via the Internet display decisive differences in how they approach this resource: either as just a way to gather data, as illustrations of theory or as a tool for reflection and testing of hypotheses. From more than 200 written student log books, student interviews and video recorded lab sessions we conclude that the students' approaches to measurements conducted through the Internet are very similar to that of measurements conducted with the students present in local classroom labs. Possible measures to support students in adopting a desirable approach to measurements are discussed.

INTRODUCTION

REMOTE LABORATORIES have recently emerged as new learning tools made possible by the rapid development of Internet technology [1]. Through remote laboratories measurement equipment can be made available via the Internet and serve either as cost-effective replacements for or as complements to traditional laboratory measurements. However, with all these new possibilities available the question is raised: What are students learning in measurement exercises? How do the students experience this new conceptual environment in general, and what is the specific experience they gain by investigating semiconductor devices via the Internet using remote measurement equipment? In this paper, we present a study where we have observed students in a course on semiconductor devices while they were trying to solve a course mini-project assignment. Our experiences are synthesized and formulated as a strategy for how we intend to use remote laboratories in the future.

The study has its origin in a department decision to improve our teaching strategy and to focus even more on the student learning environment. One part in that has been to start employing labs in which remote measurements are the essential ingredients. Reasons for this are both the intent to make more advanced equipment available to the students, equipment that we could only afford to make available through time-sharing, and to make it available around the clock throughout the course. The introduction of the remote laboratory components has been evaluated and reported [2] both in terms of student opinion, technical aspects

and course logistics. In general, the student response has been positive.

The study presented in this paper has grown out of a wish to go further and to look deeper into issues that emerged out of the evaluation process. Hereby, we could provide grounds for further development, both from a technical point of view and from the perspective of course context. We have aimed to further explore student learning experiences from working with the remote laboratory. This means addressing questions like: How do students experience the remote laboratory—do they believe they perform real measurements or is it just taken as a virtual exercise which might just as well be simulated? What is in focal awareness for students when doing (remote) measurements? How do students approach their assignment? Is the assignment formulated so that it supports the intended learning process and course objective that we, as teachers, have in mind? This process is even more important to go through if seen against the background of the scarcity of more solidly pedagogically based studies of student learning in the laboratory generally. Existing examples are from physics in-class laboratories only [3, 4].

BACKGROUND AND COURSE CONTEXT

The most important goal we have set for the course where we use these remote measurement assignments is for students to understand how a transistor in general (or in particular, a metal-oxide-semiconductor field-effect transistor, MOSFET) works. In its original conception the course employs lectures, textbooks and exercises to present and discuss underlying phenomena to explain how semiconductor devices work. The

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course organization is bottom-up with respect to content: it starts with resistors and using these as a reference, diodes and transistors are explained. Originally one hands-on laboratory exercise accompanied each of these course modules. In the present study the only 'real' hands-on laboratory exercise that remains concerns transistors, and this exercise is not linked to the examination of the rest of the course. Step by step the theoretical background is presented and the concept of device modeling is discussed. Finally, this leads to a description of the transistor function and a device model. Examination is mainly focused on the written exam at the end of the course.

In terms of assignments the students work in groups of four and receive individual grades in a project that contains three parts:

1. Resistor simulations.
2. Diode characterization on the Internet.
3. Transistor (MOSFET) characterization on the Internet.

The diodes are available via a server at Chalmers [2], and the transistors have been made available through the WebLab set-up at Massachusetts Institute of Technology (MIT) [1]. Pure electrical characterization, as in this case, makes the difference between remote and local control and read-out almost only a matter of distance and accessibility; there are no moving parts or much physical interaction involved in the laboratory tasks anyway [5]. The (resistor) assignment is examined by a short written report, the second (diode) assignment by a short oral presentation to peers, while the third (transistor) assignment is examined on an individual basis in an oral discussion led by the examiner but where the whole group is present. For the two latter assignments there is no scheduled supervision available for the students, and the group is entirely free to plan and perform their task as they choose. Some kick-off support is provided in conjunction with the first assignment, and a web forum is available for problem discussion. One supervising teacher answers e-mail questions or can be approached in person on student initiative. For a compelling description regarding the issues of tutoring in conjunction with remote lab usage see [6]. The first assignment is initiated and mainly performed under supervision in a 'studio' (where both lecturing and group computer work can occur during the same session) [7]. The project is counted as approximately 25% of the total examination directly but the content overlap to the written exam is so strong that the intended real importance of project work for examination is over 50% (making a good project work should give a strong advantage in the written exam).

The focus of this study is to gain insights into student experiences of the final part of the project: characterization of MOSFETs. In brief, this assignment was defined as familiarizing with the main aspects of the electrical characteristics of the device and to relate these to simple models. The

students were explicitly told that they were expected to be able to draw the relevant characteristics (input-, output-, and transfer characteristics) and that they must be able to describe how the measured curves compare to theoretical ones.

DATA COLLECTION AND QUALITATIVE ANALYSIS

The focus of the research reported in this study is on the students' experience of using the remote laboratories. The study is qualitative, and our objective was to understand in what context students saw the remote laboratory exercise. However, we also wanted to acquire some quantitative figures as a result of our study. At the same time we tried to keep the total amount of data and work invested in the study on a reasonable level.

For the study we decided on a strategy based on three main methods to collect information:

1. Interviews with six voluntary students.
2. Collection of student 'log books'. Students were asked to write a 'log file' briefly describing at least one of their lab sessions.
3. Video recordings. Six students (working in pairs) were video recorded while accessing and working with the remote laboratory.

The interviews and video sessions were transcribed verbatim to allow closer analysis of the students' experience. The interviews can be described as simple semi-structured interviews. Relevant topics were introduced by questions, and students were allowed to expand on the subject. Before proceeding to the next topic a number of follow-up questions were asked. For logistical reasons the interview duration was limited to about 15 minutes. The topics addressed were related to how students experienced the remote laboratory as a whole, and to how the group organized their collaboration. In particular, we investigated how students interpreted the objective of the exercise and what they perceived as the most important aspects of the MOSFET.

The objective of the video sessions was to acquire insights into how the students actually interacted with each other and with the remote laboratory in order to characterize the device under test. The video sessions were organized as follows:

- Students worked in groups of two and were monitored while working together on some part of the assignment while using the remote laboratory.
- Two cameras were used, one monitoring the students, and one monitoring the computer screen.
- The six students in this study had volunteered to be recorded and were instructed to work with the computer as they normally do with the addition of trying to articulate their thoughts

and their actions while working with the assignment more explicitly than they otherwise would.

Most students (>200) responded to the request of writing a logbook (submitted as an e-mail) of their work with the remote laboratory. In these logbooks students described their experiences from one remote laboratory session of their own choice. They also answered a number of questions on who they worked with, on how they prepared, on what strategies they used, and on what was accomplished during the session. They were also asked to summarize their experiences and to keep track of the time they spent on the assignment. The size of the student logbooks varied considerably as well as the level on which their reflections were kept.

The analysis was primarily done by examining the available material in search of statements, quotes or passages, which could give us insight into or illuminate three main questions:

1. What are the significant differences in how the 'real' hands-on transistor assignment and the remote lab assignment is experienced?
2. How do the students spend their time using the remote laboratory?
3. From what perspective do the students approach the remote laboratory assignment?

The acquired material was then interpreted and condensed. The material was substantiated into observations regarding our three main questions, and also into categories describing students' approaches as well as into suggestions for possible measures. The video sessions were the prime ground for the observations; the interviews were the most important ground for the categories. The log books gave a bulk insight into both of these aspects. With these characteristics our method is loosely based on a phenomenographic approach [8, 9] in a naturalistic setting, and in some ways resembles a naturalistic study [10].

RESULTS

On the basis of our empirical material we formulate three observations, which have implications for the implementation and organization of remote laboratory exercises in the context of the course.

Observation 1: If it can break, it can't be fake

The students seem to be treating the remote laboratory as 'real' and not as artificial simulations. This is evident both from the video sessions and from the experiences shared in interviews. The students put the remote laboratory experience on the same footing as classroom laboratories. The potential possibility of the electronic device breaking down during measurements seems to be particularly important for the sense of 'realness'. Device breakdown was reported by a number of students. One group said during the interview session that:

At first we thought it was more of a simulation, but on other occasions when it had crashed *laughter* [...] then you really felt that it was a transistor you were measuring on. [Interview 4]

In the logbooks we have the following example of a related experience:

14:30. Third time running. The first measurements proceed quite fast and we get nice plots. You can clearly see how the collector current varies with the different gate voltages. But when we measure on the gate-current we get a quite funny result with the current 'jumping up and down'. But since the current is very small and I think it really shouldn't be any current there, we treat it as negligible. When we are to measure the current as a function of the gate voltage, we get a strange result there as well. The plot does not look at all as we expected and when we plot the square root of the current as a function of the gate voltage we do not get a linear relationship, which we should get. Additionally we get some form of 'mild current rush' (that is that the current makes a big jump to a higher current) when we stepwise increase the control voltage to 3 V. Furthermore, the current at that point is on the same level, independently of the voltage V_{DS} we set. J thinks that the transistor is broken, but we think it is strange that we get any result, and we decide to bring the result and check with someone who knows, or ask on Friday. Now, in retrospect when we know the transistor was broken, we could have measured on the other transistor that was available, but we just didn't think about it at the time. At about five we finished and anyhow felt pretty satisfied. [log]

From what we can judge, devices breaking down are important learning occasions concerning what is a reasonable measurement or not. However, from students belonging to the reference group that were allowed to perform both remote and traditional hands-on measurements on MOSFETs we had reports on different focuses. In traditional classroom laboratory sessions more time is spent on practical matters like physically handling the oscilloscope and measurement instruments. From the interviews:

How did you experience it [the classroom laboratory exercise]?

It was incredibly good, we [needed] perhaps a little more time, I think, perhaps more supervision and so on; it was very directed towards set stations; we moved around and things . . .

Did you feel prepared for the classroom lab exercise?

I did feel we were prepared in such a way that, we understood everything, but something that we weren't prepared for were this insanely dangerous apparatus that you were supposed to adjust the oscilloscope with. It took basically more than half the time before we understood, because it was . . . in the way, so to speak.

What was the value of working with WebLab then?

I could imagine that for other groups it had much value, but for us it actually just felt like repetition, and really, we probably could have done our presentation of the MOSFET without that exercise, but of course it is always fun to have something to tinker with when you feel like applying a voltage to the bulk or something on the MOSFET, it is always fun to see what happens then.' [interview 3]

Our conclusion is that, complemented by physically measuring on devices, the remote laboratory gives an experience similar to a traditional laboratory. When using the remote laboratory it actually seems like the students' experience of the measurements is more focused on the function of the device, which is the central pedagogical part of the laboratory exercise. And with respect to the general purpose of including measurements, they seem to have an extraordinary illustrative power, and are experienced by students as developing their understanding.

As one student wrote in the log:

The most striking thing I have learnt (after having seen it in a measurement and then read in the book about it) is that there can be current even without voltage on the gate.

Observation 2: Make it plot on the spot

The video sessions clearly show that a significant portion of the students' time is spent on technicalities, e.g., moving data from one program to another, or writing code to plot data. This is confirmed by the logs, in which students report on whole sessions of perhaps four hours spent on some technicality. In some ways this is hardly surprising, and some time spent on those tasks is inevitable. However, we doubt that this contributes to the students' conceptual engagement and would like to reduce it (without reducing the openness of the students' task). Integration of both the interface to the experimental set-up and associated useful tools (e.g., for plotting) into one common resource is one way of paving the way for the students in this respect [6].

Observation 3: How do they do?

In the video sessions, as well as in the interviews and the logs, it is clear that there is a large variation in how students approach and handle the remote laboratory and consequently in the learning outcome. For some students the remote laboratory seems to be an advanced illustration to the textbook, for some it is more of a verification that the textbook is 'correct' in its details and claims. Some students approach the laboratory as an unnecessary evil, while some see it as a central resource for reflection on aspects of the function of transistors. Of course we find some of these approaches more productive than others. We have tried to articulate these differences to the students when handing out the assignment. Afterwards, we have analyzed the outcome further and tried to categorize the different ways of understanding the measurement component of the laboratories; we have discerned four qualitatively different ways of understanding the measurement, or different foci when the students have engaged in the remote laboratory task.

1. *Imaging what to learn.* The first way of dealing with the measurements is to focus single-mindedly on the production of some plots. The learning outcome is rather limited and the students' understanding of what the diagrams

mean is rather fuzzy. At most one could hope that the remote lab measurements serve as an inspiration to further studies next week (or closer to the examination).

When we had met and captured the plots, that now we have to read up about this and that and see if we can find any explanation [. . .] and then we gave hints for pages, also, if someone found a graph on a particular page, then we could say to the others, look on this page and try to understand. [Interview 1]

Have I learnt anything? I have learnt how I_D depends on V_D . But since I don't have any knowledge yet of why the curve looks like it does it feels like quite pointless information, I will read more of the theory the coming days. [log]

2. *Theory illustrations.* The second focus is on the theory, and the measurements are seen only as illustrations, let be slightly more advanced than the diagrams in the book.

What is it you see when you are working with WebLab?

Eehm, well, I can't answer for everybody else, but I tend to compare with what would theoretically happen when thinking about MOSFETs directly [. . .] and then you can sit and try to figure out what it should look like [. . .] and then there is an answer when you run it. [Interview 5]

You knew since one has been studying for the exam quite a lot, and then you knew quite a few characteristics compared to theoretical characteristics or to itself, but it was pretty interesting to see how it actually was, ehm, it is the biggest gain, sort of, that you got to see a real transistor in action. [Interview 4]

We prepared by having some coffee and thinking about what we knew. With help from assorted material from different courses we managed to cover how the transistor model was constructed. Then it was up to us to try to verify these theories. We tried to get the parameters that were needed to include the second order effects that the model is trying to show. [log]

3. *Iterative progress.* The third focus is partly on the measurements, partly on theory. Students adopting this approach are trying to get a feeling for the function of the device. In this case there is room for fruitful transitions from measurements to theory and from theory to measurement.

It is when new questions arise, when you think you have understood everything, then you read it again, and then new questions surface and you can get them either confirmed or corrected if you enter the lab, on the WebLab and measure. But it is more or less only measured results that is shown, and it is really not a teacher standing there telling you that the mobility changes or anything like that, but if you have got anywhere in the course, then you can come to those conclusions on your own, I think. [Interview 3]

With WebLab we sat and tried different values and saw how the MOSFET behaved for the parameters. [Interview 2]

The main point I think is that you can do a measurement more or less based on something you have seen in the book for example and see that I get something more or less the same, and then I could change the parameters and see what happens if I change something from what we saw in the book. That you can't do in the book, and more or less put a question to the program. [Interview 6]

We used the different graphs and step by step went through the origin of the current and how the different voltages affected the depletion region, mobility and such things. Then from that, we tried to make certain conclusions. [log]

4. *Hierarchical bottom-up characterization (reflecting around what is measured in relation to what is modeled)*. This fourth category emerges from the discussion between the authors of this paper, and it was not found in the collected data. It is a desired way of approaching WebLab and the assignment— to focus on the measurements and characteristics in terms of the measurement results themselves, using WebLab actively to build knowledge with support from the surrounding context.

The following (fake) quote illustrates this way of understanding the measurement

To start with on this level, we could describe it with two straight lines, it gives us the form; it has slightly different behaviors in two different areas. A straight line, we can understand quite clearly in current-voltage characteristics: drift. In between there is some form of transition. Perhaps we can change scale to understand what is happening to a logarithmic scale [. . .] here we can also see one part as a straight line, thus it is some kind of exponential behavior. We could compare that with self-generating growth, like bacteria.

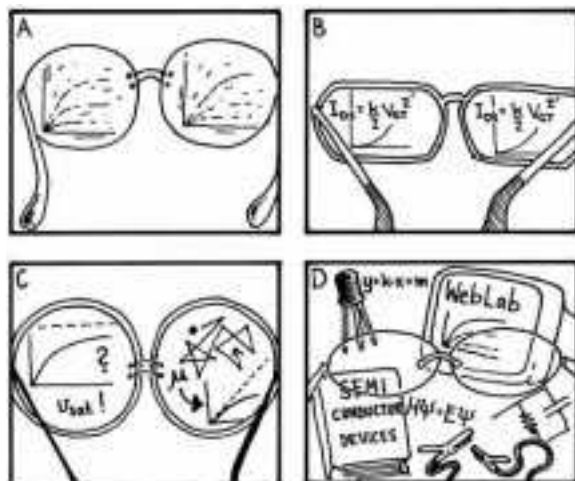


Fig. 1. Illustrations of the four different categories A-D. In A, the focus is single-mindedly on some measurements, the rest is quite blurry. In B, the theory is the lens through which the illustrative measurements are seen. In C, theoretical concepts and measurements are related to each other, and several things are in focus simultaneously. In D, it is more about seeing what is there and using the resources available to make sense of the measurements.

Another way of describing these categories is presented in Fig. 1, where we employ the simile of different glasses for the four different approaches.

DISCUSSION—POSSIBLE MEASURES

We would like to support the students in developing a feeling for the function of the devices, having a focus on measurements as a starting point for modeling work, as well as seeing that as a goal of their learning. To put it succinctly, we would like the students to develop a way of relating to the measurement on components as is described in category D above. In the light of this category the characterization of an electronic component includes the continuous and systematic shift between different appropriate scales and ways of organizing the characterizing data: now in a plot of the I_D versus V_G ; now in a plot of I_G versus V_G ; now in a log-lin plot of current versus voltage; now with several curves in the I_D - V_G diagram; now in an up-scaled part of the I_D - V_G plot, as some examples.

The implications of changing the course to have this as an important goal may be far-reaching for the total structure of the course. One way to do that could be to introduce a lab exercise, which is allowed to play a big part in the course, while other parts will become less focused on. The suggested assignment is structured in two parts:

1. Students get the task to measure on an unknown device and some indications on what might be relevant to measure. The task is not only to make measurements but to describe them in such a way that a reader (of the description) can understand what the measurements look like. If possible we want the students explicitly to change perspectives, scaling, etc., to find the most relevant way of describing them, where there are clear characteristics which make them distinct from other measurements. The report should be brief, with other students as the set audience. Preferably there will be several different unknown devices to choose from, out of which the students can measure on one. The students may (or may not) be organized in groups. To make the task more challenging, a requirement may be that the report should not have any explicit graphical information.
2. Students hand in their report and get someone else's report in return. The second part of their task is to make conclusions on the basis of the received report about what kind of device that was measured on and motivate these conclusions. If that is too difficult, the task is instead to critique the report and explicitly explain why there is not enough information to make conclusions (and as far as possible to give

indications of what information is missing). For example, if the information points towards two possible components, a task could be to point out which distinguishing information that is missing. Finally, they should give feedback on the report according to certain criteria set by the course teachers (a form of peer evaluation). An additional part of the task could be to do measurements for reference on a known component and show how the given description matches these measurements.

Such structuring can be related to what Lippmann [4] expresses as a goal for the changes she has done as a consequence of her research: to 'teach students to utilize their everyday skills of argument and decision-making for data gathering and analysis'.

We will start off in this direction, trying to use smaller measures to start with. The focus will initially be on addressing problems related to what is (or hitherto has been) assumed to be previous content knowledge for the students. That means reflecting on what has actually been included in previous courses and in what way the students have learned basic key foundations and to identify basic stumbling blocks (e.g. to have an

idea how a plot changes when changing from a linear to a logarithmic scale).

CONCLUSIONS

From our investigation it appears that students approach measurements through a remote lab in much the same way as in a local lab environment. Much time is spent on data management. We can discern four qualitatively different foci for the students when engaged with their remote lab tasks, and we believe that the learning outcome can be promoted by helping students finding the most appropriate focus. We conclude that the remote laboratories in practice mean access to an abundance of cheap measurements and using them may allow pursuing other aims than we could do otherwise. For the specific object of learning considered in the present course, hands-on laboratory exercises might not be needed.

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