Characterizing a Thermoelectric Module as Part of a Semiconductor Course Laboratory

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***Abstract*—Thermoelectric modules (TEM), also known as Peltier modules, form an interesting topic to cover in an introductory semiconductor course. They provide insight on some important semiconductor principles, namely the Seebeck effect (the reverse of the Peltier effect) and thermal conductance. This paper presents a new methodology to characterize a TEM using a custom-designed test apparatus along with a simplified method for determining the TEM's three key parameters: its Seebeck coefficient, its electrical resistance, and its thermal conductance. Results obtained using this methodology were validated by comparing the anticipated theoretical behavior of the TEM (using the experimentally determined parameters) to the actual results obtained in a vacuum environment. The suggested methodology has been evaluated by students and the results of this demonstrate its usefulness in an educational environment.**

***Index Terms*—Peltier module, semiconductor laboratory course, thermoelectric module (TEM), thermoelectric parameters.**

I. Introduction

Thermoelectric modules (TEMs) have become one of the most prevalent ways of cooling. Consisting of series-connected semiconductor thermoelements [1], TEMs allow precise cooling or heating of an entity by varying the amount of electrical current that flows through them. They are especially useful in applications requiring temperature control, small size, light weight, precision, and reliability [2]. Typical examples of their use as a heat pump are central processing unit (CPU) cooling, recreational coolers, and infrared sensor cooling. Their widespread utilization makes them candidate topics for an introductory first- or second-year semiconductor course. TEMs are especially suited to be the main subject of a laboratory class since their underlying physical principles can be directly observed and understood by the students.

Present characterization methods [2]–[4] are not suitable for use by inexperienced students within the confines of a laboratory session lasting at most three hours. The difficulties encountered in applying existing modeling techniques to a lab experiment is that they require many complex steps that are difficult to grasp firsthand and that require close supervision.

This paper presents a new and simple parameter extraction methodology to determine experimentally the Seebeck coefficient, the thermal conductance, and the electrical resistance of the TEM. The advantages of this methodology are the ease of application and the intuitiveness of the process.

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The proposed methodology can be divided into two distinct parts: 1) the simplified parameter extraction process, which is based on the mathematical manipulation of known TEM equations and 2) the experimental test apparatus that is used to retrieve the experimental data needed for computation. As will be shown, the results obtained are sufficiently coherent and rigorous to validate the application of the suggested methodology for educational purposes.

In Section II, the course background and objectives are described, while Section III covers the proposed parameter extraction process and Section IV details the test apparatus. A demonstration of an application is given in Section V, while experimental validation is conducted in Section VI.

Finally, the results of a student survey are provided in Section VII as a means of evaluating the proposed methodology in its designated environment.

II. Course Background, Description, and Objectives

As previously mentioned, the proposed test apparatus and related experiment are suitable for first- or second-year introductory semiconductor courses. The particular course for which this laboratory experimentation has been developed is a second-year semiconductor physics course titled Semiconductor Devices and Optoelectronics. The main objectives of this course are the following:

- describing the structure of semiconductor materials;
- interpreting the electron band structure;
- explaining the electrical and thermal behavior of the materials;
- explaining the mechanisms behind basic semiconductor and optoelectronic devices;
- linking the optical properties of semiconductors to electron band structure.

More specifically, the objectives of the laboratory part of the course consist of the following:

- experimentally introducing the mechanisms of electrical conduction in semiconductor materials;
- measuring the I-V characteristics of basic semiconductor devices;
- deriving the various physical parameters of the devices from the measured I-V characteristics.

The suggested experiment fulfils all these laboratory objectives by the following:

- providing evidence of electrical and thermal conduction in semiconductor materials due to the Peltier effect;
- asking students to measure and plot characteristics that pertain to the TEM;
- asking students to deduce the various physical parameters of the TEM based on the measured characteristics.

In addition to being part of the proposed experiment, the custom test apparatus is used for a second laboratory experiment in which the TEM subjects semiconductor devices to temperature variations.

III. Simplified Parameter Extraction Process

A comprehensive parameter extraction process must first be defined, that allows the students to use the retrieved data in order to compute the three TEM parameters in question. The extraction process is based on a very popular and widely known electrothermal model. The following subsections detail the suggested process.

A. Electrothermal Model

The complete steady-state TEM behavior can be represented by two equations [3]. The first one treats the heat transfer balance between the cold and the hot sides

$$Q_c = \alpha I_p T_c - 0.5 R_p I_p^2 - K_p \Delta T \tag{1}$$

where Q_c is the heat transferred from the cold side, α, K_p, R_p, are respectively the TEM's average Seebeck coefficient, the average thermal conductance, and the average electrical resistance, I_p is the electrical current flowing through the TEM, T_c is the cold side temperature, and ΔT is the temperature difference between the hot side and the cold side ($T_h - T_c$). The second equation describes the electrical properties of the TEM

$$V_p = I_p R_p + \alpha \Delta T \tag{2}$$

where V_p is the voltage found at the terminals of the TEM.

Equation (1), however, neglects the heat transferred by convection and radiation through the air that surrounds the TEM, as pointed out by [3]. As a result, test apparatuses designed by [3] and [4] respectively used a temperature-controlled vacuum environment. Nonetheless, the accuracy of (1) and (2) are satisfactory for educational purposes, as will be shown in Section VI.

B. Existing Parameter Extraction Processes

The existing parameter extraction processes described in [2] and [4] have inherent limitations that preclude their application in an educational laboratory experiment. While the existing methods are efficient at characterizing a TEM by precisely obtaining the three targeted parameters, they are not directly suited to educational purposes.

In [2], the Seebeck coefficient and the electrical resistance are extracted using the modified Harman method [5], whereas the comparative method [6] is used to find the thermal conductance, K_p. This two-step process yields credible results, but is arguably too demanding to be carried out during a laboratory session.

The parameters in a tightly controlled environment were extracted in [4] by setting $I_p = 0$ and imposing an arbitrary temperature difference ΔT to simplify (1) and isolate successively α, K_p, and R_p. This methodology offers reasonable results, but does not provide *average* parameter values, as they are subject to variations if different temperature values are used. Hence, these results cannot be used to characterize the TEM fully over a wide temperature range. Moreover, (1) and (2) require the use of average parameter values in order to be valid, as stated in [2].

C. Suggested Parameter Extraction Process

The suggested parameter extraction process is based on subsequent basic fittings of experimental data. A linear fitting is used to retrieve the electrical resistance, while a second-order fitting is employed to extract the thermal conductance and the Seebeck coefficient.

Examining (2), it is seen that for a constant temperature difference, ΔT, plotting V_p as a function of I_p results in a linear function whose slope corresponds to R_p, the desired electrical resistance. Thus, to obtain R_p it is only necessary to sweep I_p over a range of predetermined values and measure the corresponding V_p while maintaining a constant ΔT. The latter condition can be achieved by providing heat to the cold side. Note that the constant value of ΔT must be chosen to be equal to that measured when I_p has the lowest nonzero positive value of the swept range. This precaution ensures that ΔT will always be positive, and can be held constant while taking the measurements by heating the cold side.

The extracted value of R_p is required for the second step of the extraction process, which involves a second-order extrapolation. From (1), nulling the heat on the cold side ($Q_c = 0$) and dividing by T_c^2 leads to a second-order polynomial

$$\underbrace{\frac{\Delta T}{T_c^2}}_{y} = \underbrace{\left(\frac{\alpha}{K_p}\right)}_{p_1} \underbrace{\left(\frac{I_p}{T_c}\right)}_{x} \underbrace{-0.5\left(\frac{R_p}{K_p}\right)}_{p_2} \underbrace{\left(\frac{I_p}{T_c}\right)^2}_{x^2}. \tag{3}$$

Thus, for a given set of ΔT data and by keeping T_h constant with $Q_c = 0$, one can execute a second-order fit to determine p_1 and p_2. Then, the thermal conductance and Seebeck coefficient are found using the following equations:

$$K_p = \frac{-R_p}{2p_2} \tag{4a}$$

$$\alpha = p_1 K_p. \tag{4b}$$

Since (3) assumes that the temperature difference equals zero ($\Delta T = 0$) when there is no current flowing through the TEM ($I_p = 0$), the second-order fitting process should be compensated by nulling the constant coefficient ($p_0 = 0$). This allows p_1 and p_2 to represent the optimal fit while ensuring that the fitting curve passes through the origin.

IV. Proposed Test Apparatus

The test apparatus facilitates the data retrieval process by allowing measurement of the temperatures of both the cold side and hot side of the TEM, along with the electric current and the corresponding operating voltage of the TEM. It comprises both a heat-dissipation device, and a means to control and measure both the cold and hot side temperatures.

In an educational environment, the test apparatus has to be low-cost (as a few dozen units are required), rugged, easy to operate and, as much as possible, maintenance-free. The existing test apparatuses found in the literature are excellent for providing rigorous results, but they are not well-suited for educational purposes. The suggested test apparatus is simpler, easier

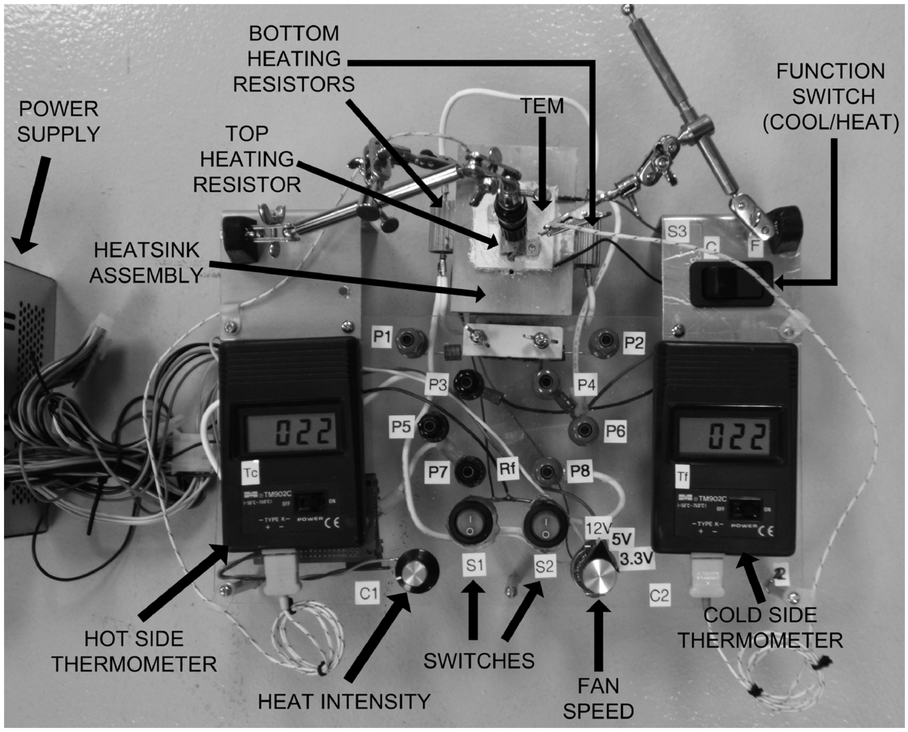

Fig. 1. Photograph of the test apparatus.

to operate and cheaper to implement and maintain. The following subsections describe the existing and the proposed test apparatuses.

A. Existing Test Apparatuses

The test apparatuses described in [2]–[4] have limitations to their application in an educational laboratory experiment.

A computer-driven test apparatus comprising a large aluminum heat sink assembly placed in a temperature-controlled chamber is presented in [3]. Such a configuration is unpractical in an educational scenario due to its high cost and complexity. Also, [3] uses long (50 to 300 seconds) time constants in order to ensure that the tests are performed under steady-state conditions, something that is not possible in a restricted and fixed time frame.

Similarly, [4] uses a test apparatus consisting of a computer, two control valves, a constant-temperature bath with a mechanical pump and a large vacuum jacket. The complexity and cost of this test apparatus renders it impractical for educational purposes.

On the other hand, [2] introduces a mechanically simpler test apparatus that uses a polyurethane foam surrounding to protect against ambient conditions. In spite of this, the use of a second TEM is required in order to cool the tested TEM. This addition is costly, mainly because a second power supply unit is required to operate this setup.

B. Suggested Test Apparatus

Fig. 1 is a photograph of the test apparatus. It consists of a Plexiglas frame to which the elements are mounted. In order to satisfy the power requirements of the cooling fan and heater circuits, a computer-type power supply is connected through a multiterminal wire port. Note that the purpose of this power supply is not to deliver energy to the TEM. Indeed, because of the various possible TEM current and voltage ranges, it is advisable to select an external power source (not shown in Fig. 1) that satisfies these requirements more precisely than does the apparatus' own supply. Furthermore, a separate supply allows a more precise measurement of the TEM electrical current, and reduces the cost of the suggested test apparatus by omitting an instrument that is already found in most electrical engineering laboratories. Terminals P1, P2, and P3 (common) are used to connect the external supply unit. To ensure that the TEM current flows in only one direction, and to facilitate the use of two distinct external power supplies, P1 and P2 are parallel-connected and isolated by power diodes. Terminal P4 is directly connected to the positive lead of the TEM to allow a precise voltage measurement that is not influenced by the diodes of the P1 and P2 circuit.

The Plexiglas frame is screw-mounted to a computer-grade heatsink assembly on which the TEM sits. To improve heat dissipation and to provide a means of varying the quantity of heat dissipated, a fan is located at the bottom of the heatsink. Its speed is controlled by the fan speed knob indicated on the picture. Since the test apparatus receives power from a typical computer-type power supply unit, the fan speed is restricted to three voltages, $+3.3$ V, $+5$ V, and $+12$ V.

The computer-type power supply also provides energy to the TEM heating mechanism, consisting of a custom-designed pulsewidth modulation (PWM) switching modulator and three heating resistors. The modulator allows the heating power to be adjusted with the heat intensity knob indicated in Fig. 1. Power resistors are connected to PWM output terminals P7 and P8 by using wires. Switch S2 turns the PWM modulator ON or OFF, while switch S1 delivers power to the fan and the switch S2. This ensures that the PWM modulator will not be used to heat the TEM while the cooling fan is inactive.

Located on the cold side is a single resistor positioned in the middle of the plate and firmly held in place by a plastic terminal located at the end of a flexible arm. As the resistor is not permanently installed, it can be removed when not in use in order to reduce thermal loading on the cold side.

Two additional heating resistors are positioned on the sides of the heatsink assembly, to provide heat to the hot side if need be. These resistors are connected in parallel to terminals P5 and P6. Note that thermal compound is used on both contact areas of the TEM to ensure maximum heat conduction.

The TEM is electrically connected to a three-way pivot function switch that enables the device to operate in normal cooling mode ($T_c < T_h$) or in a heating mode ($T_c > T_h$) by simply reversing the polarity of its supply. The latter mode can be used as part of a lab experiment in which a semiconductor device has to be submitted to a temperature ramp. The function switch is connected to the external power supply through terminals P1 and P2.

Temperature measurement is performed by two digital, battery operated thermometers using K-type probing devices. The probes are placed using alligator grips to ensure a stable contact with the TEM. In order to facilitate battery changes, thermometers are held in place using Velcro strips.

V. Demonstration of Application

A widely available Melcor HT6-12-40 TEM [7] was selected as the device under test for a demonstration of the proposed characterization methods. Values of I_p ranging from 0 A to 5 A are used, as they cover most of the allowable current range as specified by Melcor, while leaving a 1 A safety margin. Also, subdivisions of 0.25 A are chosen in order to provide a sufficient number of measurement points. However, tests have shown that students may use a lesser amount of points without greatly compromising the values of the resulting parameters.

As was explained in Section III, the first step in characterizing the TEM is to determine its electrical resistance. To do so, students have to measure the voltage across the TEM terminals for the given current range, while maintaining a constant temperature difference between the hot and cold sides, ΔT. This constant temperature difference has to be measured at the smallest positive current which, for this example, is $I_p = 0.25$ A. The value found was $\Delta T = 3$ K, and it was held constant through the measurements with the help of the heating resistor on the cold side.

According to (2), the resulting curve of the voltage plotted against the electrical current should be a linear function where its slope corresponds to the electrical resistance of the TEM, R_p. Fig. 2 illustrates the experimental results (dots) and the linear fit (solid line) used to retrieve the slope, p_1. Since the only fitting coefficient of interest is the slope, the constant fitting term, p_0, is ignored.

The second step in characterizing the TEM is to determine the thermal conductance and the Seebeck coefficient. To accomplish this, students first have to remove the heating resistor from the cold plate to enforce the condition $Q_c = 0$ W. They are then asked to measure ΔT for I_p varying from 0 to 5 A, while maintaining the hot side temperature, T_h, constant to the value measured when I_p is set to its maximum value. In this example, T_h was evaluated at 344.15 K for $I_p = 5$ A and it was held for all the measurements. After collecting the data, students employ (3) to plot a quadratic curve and perform a quadratic fit, as shown in Fig. 3. As mentioned in Section III, the constant coefficient of the quadratic fit (p_0) must be forced to zero in order to reflect the physical reality of the TEM. In order to improve the accuracy of the fit, a larger data point density was chosen for the lower half of the range of I_p, where the greatest slope is encountered.

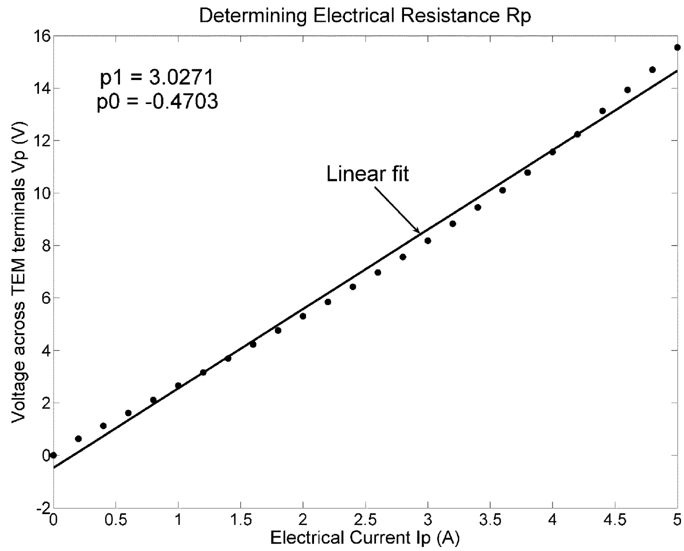

Fig. 2. Determining the electrical resistance of the TEM using a linear fit.

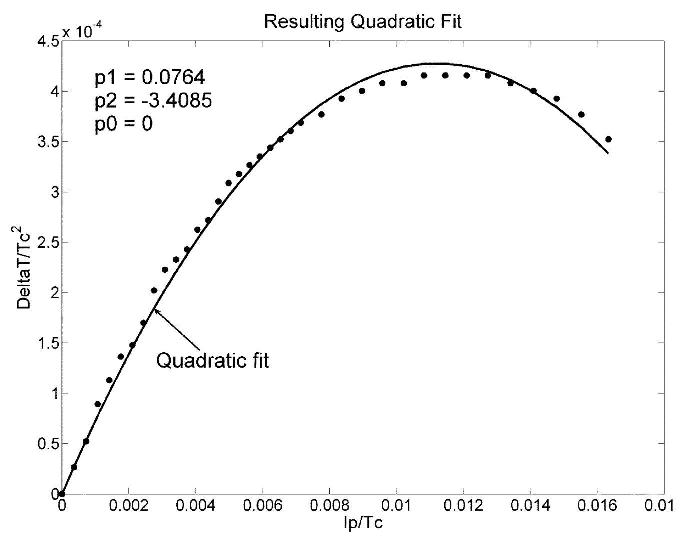

Fig. 3. Resulting quadratic fit based on (3).

Finally, using (4) and the resulting second-order parameters (p_1 and p_2), the thermal conductance and Seebeck coefficient are found to be $K_p = 0.4440$ W/K and $\alpha = 0.0339$ V/K.

VI. Experimental Validation

Having fully characterized the TEM, it is interesting to verify whether the theoretical plot of ΔT against I_p under the condition $Q_c = 0$ W matches the experimental curve from which

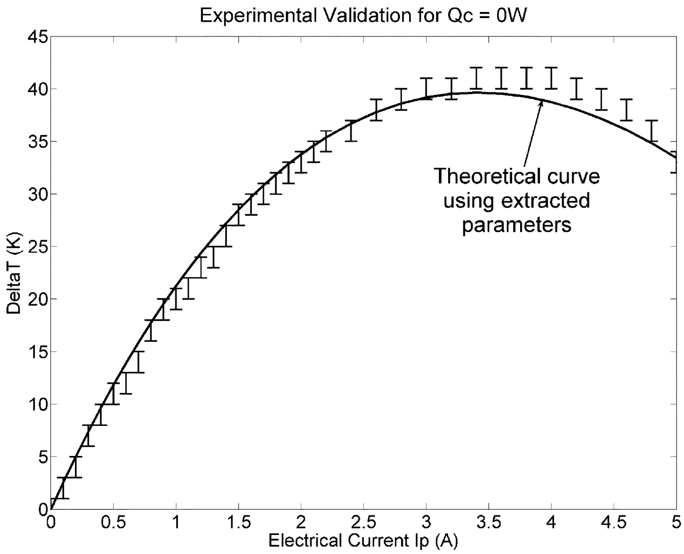

Fig. 4. Experimental validation for $Q_c = 0$ W.

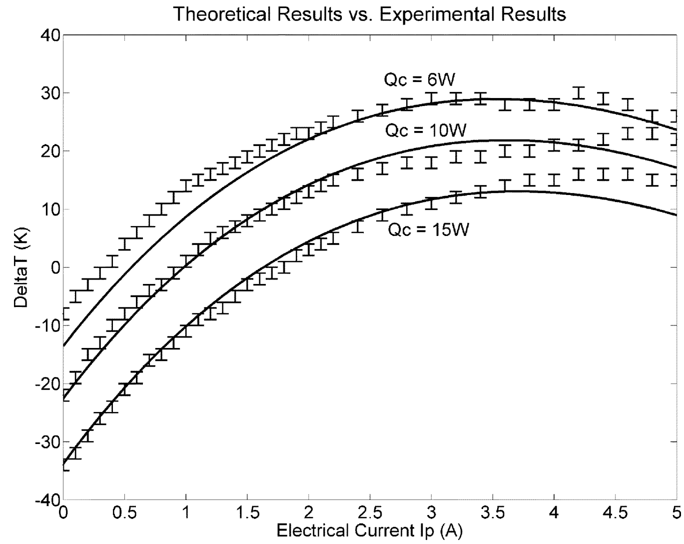

Fig. 5. Comparison of the expected theoretical results using the proposed characterization method (plain lines) and experimental data obtained under vacuum conditions (error bars).

the parameters were deduced. Such comparison is a useful indication of the quality of the characterization since it takes into account all the derived parameters, including R_p which is not part of the fit shown in Fig. 3.

Rearranging (1), it is possible to determine ΔT as a function of I_p for different values of Q_c by means of the following:

$$\Delta T = \frac{\alpha I_p T_h - 0.5 R_p I_p^2 - Q_c}{K_p + \alpha I_p}. \tag{5}$$

Fig. 4 illustrates the resulting theoretical curve from (5) with $Q_c = 0$ W compared to the experimental data. As could be anticipated, the resulting theoretical curve fits properly since two of the three TEM parameters were deduced from this set of data. Note that the two thermometers used for measurements exhibit ± 0.5 K resolution accuracy. As a result, the nominal error value is ± 1 K as shown with the error bars.

In order to further verify the results obtained by the suggested methodology and test apparatus, three theoretical curves using (5) considering different amounts of heat, Q_c, were compared to experimental data obtained under vacuum. The latter condition was observed in order to minimize power dissipation through ambient air, which was mentioned previously as a necessary assumption for (1) to be valid. In order to create a sufficient vacuum, a sealed Plexiglas box was epoxy-glued over the heat sink on the test apparatus, and a vacuum pump was used to remove the air continuously from the box.

The data was subsequently plotted by applying the desired amount of heat to the cold side, Q_c, and sweeping the electrical current, I_p, over the selected range (0 A to 5 A). The following values were chosen for Q_c: 6 W, 10 W, and 15 W, as they remain well under the maximum capacity of the TEM. The results are presented in Fig. 5.

As can be observed, the experimental results validate both the theoretical assumptions and the suggested parameter extraction process. This is especially true for lower values of current, i.e., $I_p < 3.5$ A. The error becomes more important as I_p increases over 3.5 A. This behavior is assumed to be directly related to the parameter extraction process, since Fig. 4 also shows a slight mismatch for upper values of I_p. Another significant cause of error is the imperfect vacuum condition, which leads to undesired heat dissipation in air. Nonetheless, and in spite of its relative simplicity, the suggested extraction process yields credible results that are satisfying for educational purposes.

Question	Response			
	SD	D	A	SA
The laboratory sessions help students grasp the principles of experimental methods and their application				
The laboratory sessions are an essential part of the course				

SD- strongly disagree, D- disagree, A- agree, SA- strongly agree

Fig. 6. Part of the generic student survey used to gather student feedback about the laboratory sessions.

VII. Student Feedback

The TEM experiment described here, and the corresponding course, were simultaneously established two years prior to the time of writing. As a result, no before-and-after comparative student feedback could be obtained. Nonetheless, university authorities provide a voluntary, anonymous, and generic student survey that covers the complete semiconductor course, including the theoretical part. This survey was established by the university's pedagogical board to assess the quality of teaching and related learning activities. It was conducted over the four semesters and was divided in two parts, the first one consisting in 11 questions rated on an agreement scale, and a second one allowing students to write comments. Among the questions posed to students, two directly concern the laboratory sessions, as shown in Fig. 6.

A total of 53 students responded to the first question. Out of them, 47% strongly agreed (SA) and 42% agreed (A), which

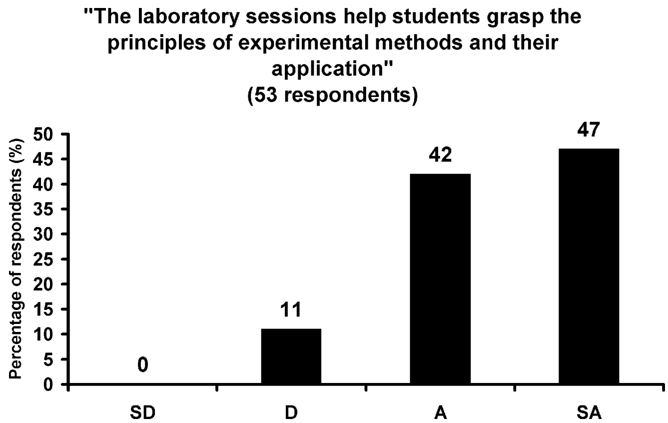

Fig. 7. Results of the survey for the first question presented in Fig. 6.

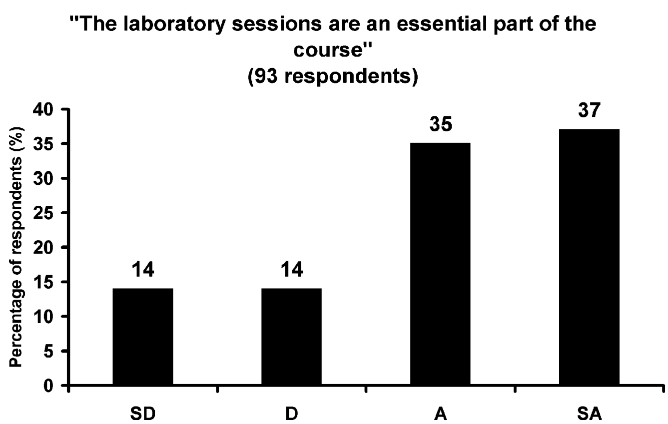

Fig. 8. Results of the survey for the second question presented in Fig. 6.

yields an 89% rate of agreement. It is worth noting that no student strongly disagreed (SD) and only 11% disagreed (D). The results are presented in Fig. 7.

For the second question, out of the 93 answers, 37% were in strong agreement and 35% were in agreement, which results in a 72% rate of agreement, as shown in Fig. 8.

Lastly, students were offered the opportunity to comment on the course and laboratory. Although very few students completed this section of the survey, the compiled answers pertaining to the lab work are encouraging. Here is a sample of student comments.

- "Lab sessions are very interesting and allow us to fully understand the subject."
- "It's a good thing that the lab work is there to keep us interested in the course."
- "Nothing needs to be said, everything is perfect about the lab sessions."

There seems to be a consensus among students that laboratory sessions, which feature the suggested TEM study, are interesting, and help in grasping important concepts.

VIII. Conclusion

A novel TEM characterization method that is especially suited to educational purposes was presented, explained, and demonstrated. Using a low-cost, low maintenance and easy to understand test apparatus, students can retrieve data efficiently in a time-limited laboratory session context. The three main TEM parameters can subsequently be extracted by means of widely available linear and quadratic fit algorithms and simple arithmetic. These parameters have been shown to provide a reasonable description of the behavior of the TEM across the range of admissible input current and dissipation power. Finally, the educational value of the proposed characterization method was assessed by means of student surveys conducted over four semesters. As a future work, it would be interesting to gauge precisely the effect of the suggested test apparatus on student learning. This could be accomplished, for example, by using comparative studies and a customized survey questionnaire.

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