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Semiconductor Device Fabrication Lab Demonstration during and after COVID-19

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CONTEXT

The Solar Cell Lab is a vital element of the popular ENEL491 Nano Engineering course offered by the Electrical and Computer Engineering at the University of Canterbury. The course and associated lab introduce and demonstrate basic semiconductor device fabrication processes to 400-level students. The lab has attracted students from multiple departments and the number of enrolled students increased from less than 20 in 2012 to nearly 70 in 2024. Students fabricate and characterise solar cells from a plain silicon wafer received at the beginning of the lab session.

PURPOSE OR GOAL

To minimize virus transmission and, at the same time, maintain the quality of the delivered teaching. To ensure students have the opportunity for sufficient hands-on experience in semiconductor fabrication processes, the measures described were implemented during the COVID-19 pandemic.

APPROACH OR METHODOLOGY/METHODS

The original arrangement of the lab demonstration was designed for fully immersive face-to-face delivery. There were 2 streams with 6 to 8 groups of students (2 or 3 per group) per stream depending on numbers. Students are expected to attend 1 stream for a duration of 3 weeks, learning different fabrication techniques. Each student will submit a report individually at the end of the three weeks of labs. After the pandemic, the maximum number of students for each stream was reduced to 6 students per stream and the number of available streams increased to a maximum of 12 streams. In addition, videos were recorded during wafer preparation and lab sessions, and made available via UC Learn, thus maintaining student engagement during mandatory COVID-19 isolation.

ACTUAL OR ANTICIPATED OUTCOMES

There are better interactions between the teaching assistants (TAs) and students after the change in the arrangement. Students are more likely to ask questions during lab sessions when the maximum student number per stream decreases. With the change in lab session arrangements, students were able to work on each process step without time pressure, allowing for a more hands-on experience, with students thus receiving more information transfer from TAs and staff.

CONCLUSIONS/RECOMMENDATIONS/SUMMARY

Before the pandemic, students were allocated less than 12 minutes per group per step. After changes were implemented, better interactions with students could be observed during lab sessions, and the TA workload could be better balanced for preparation between sessions, thus providing a better work/rest balance. Interestingly, despite challenges experienced during the pandemic, students were still able to achieve similar solar cell performance compared to pre-COVID years.

KEYWORDS

semiconductor fabrication, solar cells, practical laboratory work.

Introduction

Electronic components such as integrated circuits (ICs) have become essential components in most electrically powered devices. This includes everyday 3C products (IT, communications, and consumer electronics), home appliances, transportation, and power generation. With ever-increasing performance expectations from electronic devices, manufacturers must find ways to increase the number of electronic components on an IC chip without increasing the size of the chip. This has led to the rapid development of advanced semiconductor manufacturing technology, challenging beyond the limits of Moore's Law (Valasa et al., 2024).

Semiconductor manufacturing can generally be divided into several important steps: lithography: transferring the device design, deposition: forming a thin film of a metal or dielectric, etching: removing unwanted materials, diffusion: introducing impurities into the semiconductor to form PN junctions, and packaging: transferring the finished chip to compatible packages with printed circuit board (PCB) carriers (Ho & Shealy, 2003; May & Sze, 2004). New advanced manufacturing technologies have been introduced to produce integrated circuits with high component density, but they are generally inaccessible to university students who want to learn the relevant processes. Therefore, students in the classroom often have difficulty connecting the theories of manufacturing technology learned in class. In Taiwan, universities frequently collaborate with industrial companies such as Taiwan Semiconductor Manufacturing Company (TSMC) to teach students how to make devices (*About the Centre*, n.d). However, in New Zealand, there is a lack of industries with semiconductor production lines or suitable research and development facilities. Therefore, laboratory demonstrations in semiconductor fabrication laboratories are important for students to gain practical experience in semiconductor manufacturing.

The Solar Cell Lab offered in the Department of Electrical and Computer Engineering, University of Canterbury, is one of the essential teaching modules for final year students undertaking the ENEL 491 Nano Engineered Device course (*ENEL 491 Nano Engineered Devices*, 2024). The laboratory demonstration has been running for over 10 years, allowing students to gain hands-on experience in conventional semiconductor fabrication and related device characterisation techniques while learning from experienced technical assistants in wafer or device processing. The number of students enrolled in this course has increased from less than 20 in 2012 to nearly 70 in 2024. The laboratory has sparked the interest of several students in semiconductor manufacturing and continued research in nanotechnology after completing their bachelor’s degree.

In 2020 and 2021, New Zealand went through several lockdowns due to the COVID-19 outbreak, as did most countries worldwide. In response to the outbreak and to ensure minimum effect on New Zealand’s economy, the government announced the traffic light system in November 2021, to allow people to work or study as normally as possible while minimizing the virus transmission. However, all staff and students who have not been vaccinated with COVID-19 vaccines were banned from most institutions (Carter, 2022; Scotcher, 2021), resulting in the requirement to reorganize the solar cell lab arrangements. Numerous teaching lab arrangements from other departments either need to be cancelled or moved online due to the vaccination mandate policy and the difficulties in implementing the restrictions (McDonald, 2022; Russell, 2022), the solar cell lab managed to operate normally. Shifting the teaching laboratory modules to an online version, in general, resulted in an increased attendance crisis that New Zealand already facing for many years (Uekusa, 2023). Therefore, maintaining in-person teaching lab modules is important, especially for post-pandemic teaching in tertiary sectors.

Given that the solar cell lab demonstrations were usually held in March, the lab demonstration in 2021 was not affected. This is because despite the COVID outbreak in New Zealand started in mid-2020, the alert level at Christchurch in March 2021 was at Aler Level 1, allowing people to work normally as before COVID outbreaks This paper describes the way the solar cell lab works and how the lab overcomes the COVID-19 outbreak restrictions. Pre-Covid arrangements defined in this paper are solar cell labs completed before and in 2021, whereas post-Covid refers to lab demonstrations carried out in 2022.

Solar Cell Lab Demonstration Arrangement

The purpose of the Solar Cell Lab is for students to have practical experiences on various semiconductor fabrications. During the laboratory sessions, students will go through different fabrication stages, such as impurity diffusion, photolithography, and various device characterisation techniques, for fabricating a complete solar cell from a plain, uncoated silicon wafer. At the end of the laboratory sessions, students are required to write a laboratory report detailing the manufacturing processes, and equipment characterization results, calculating the theoretical performance of the equipment based on the provided control parameters and comparing them with the measured results (ENEL 491 Nano Engineered Devices, 2024).

Solar Cell Fabrication Process for Solar Cell Lab

The fabrication process for making solar cells in the Solar Cell Lab can be separated into several blocks: 1. Oxide window defining, 2. Impurity diffusion, 3. Metal contact patterning, and 4. Device characterisations. Before the commencement of the laboratory, the teaching assistants would process the commercially available p-type wafer, such that each wafer contains multiple 1 cm^2 isolated oxide windows, where each individual oxide window will become individual solar cells after the wafers go through the complete fabrication processes, as shown in **Error! Reference source not found.**. Due to the time constraints, only the diffusion of Boron is done during the lab session where the students can have experiences in push-in and pull-out of the wafers from the high-temperature furnace, as well as wafer handlings. The flow chart of the diffusion processes is shown in **Error! Reference source not found.**. The phosphorous diffusion and excess impurity deglazing were completed after the diffusion lab demonstrations.

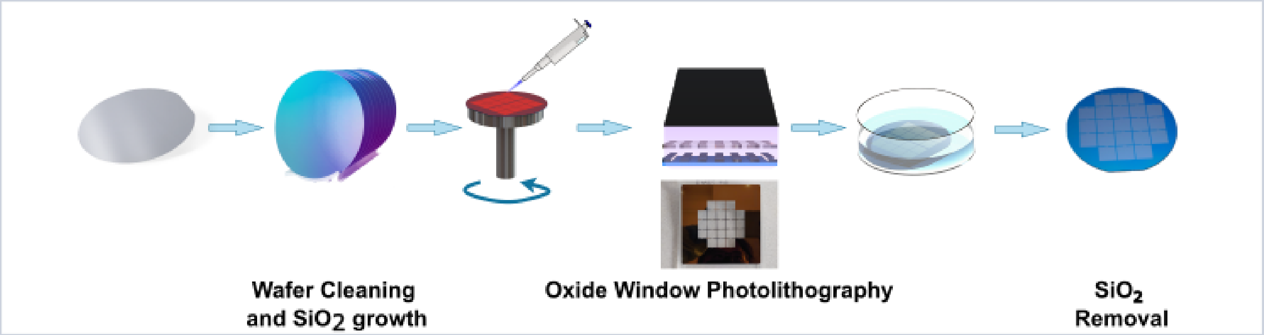


Figure 1 Wafer preparation before lab commencement.

The diffusion wafer will then pass through a metal deposition layer to contact the top metal. The students will then be able to experiment with the photolithography process for the top contact, which includes fabrication techniques such as spin coating, mask pattern transfer via a mask aligner, and metal etching, as shown in Figure 2. Next, the back metal contact is deposited, followed by an elevated temperature to anneal the metal. For the final part of the solar cell lab, students will go through various measurement stations, including measuring current and voltage under light and without light, a profiler to measure thin film thickness, busbars with superior contact and finger size, and taking images under a microscope. Figure 3 shows an example of what students have measured with the solar cell device they fabricated.

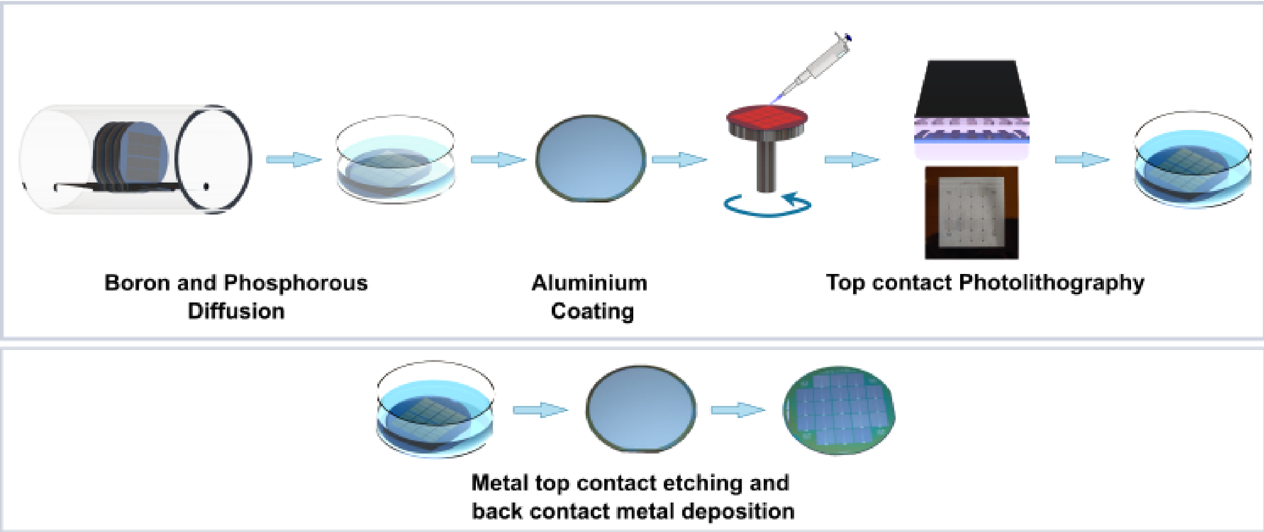
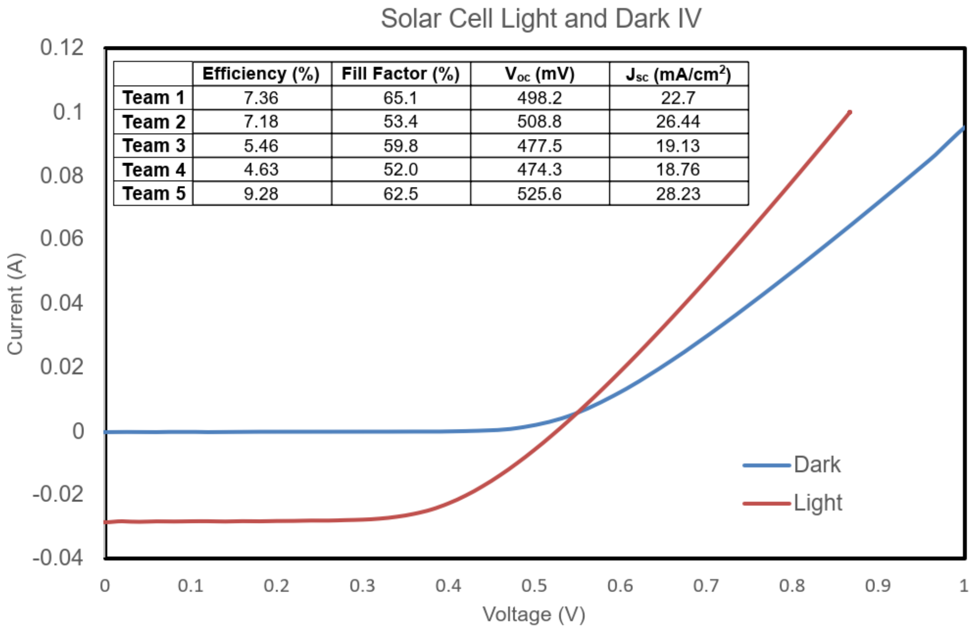


Figure 2 Fabrication processes of week 2 Boron diffusion, after lab Phosphorous diffusion, week 3 Top metal contact photolithography, and metal etching



	Efficiency (%)	Fill Factor (%)	V_{oc} (mV)	J_{sc} (mA/cm^2)
Team 1	7.36	65.1	498.2	22.7
Team 2	7.18	53.4	508.8	26.44
Team 3	5.46	59.8	477.5	19.13
Team 4	4.63	52.0	474.3	18.76
Team 5	9.28	62.5	525.6	28.23

Figure 3 A typical light and dark IV graph of the measured solar cell device done by students in week 4. Table Insert: Solar cell performance measured by students

After attending the lab sessions, students need to submit a report describing the fabrication processes of the solar cell that they fabricated and compare the device characteristics of the solar cells to the calculated performance based on the parameters provided by the lecturer and TAs. A screenshot of a student's report is shown in Figure 4, describing the process of aluminium wet etching and photoresist removal.

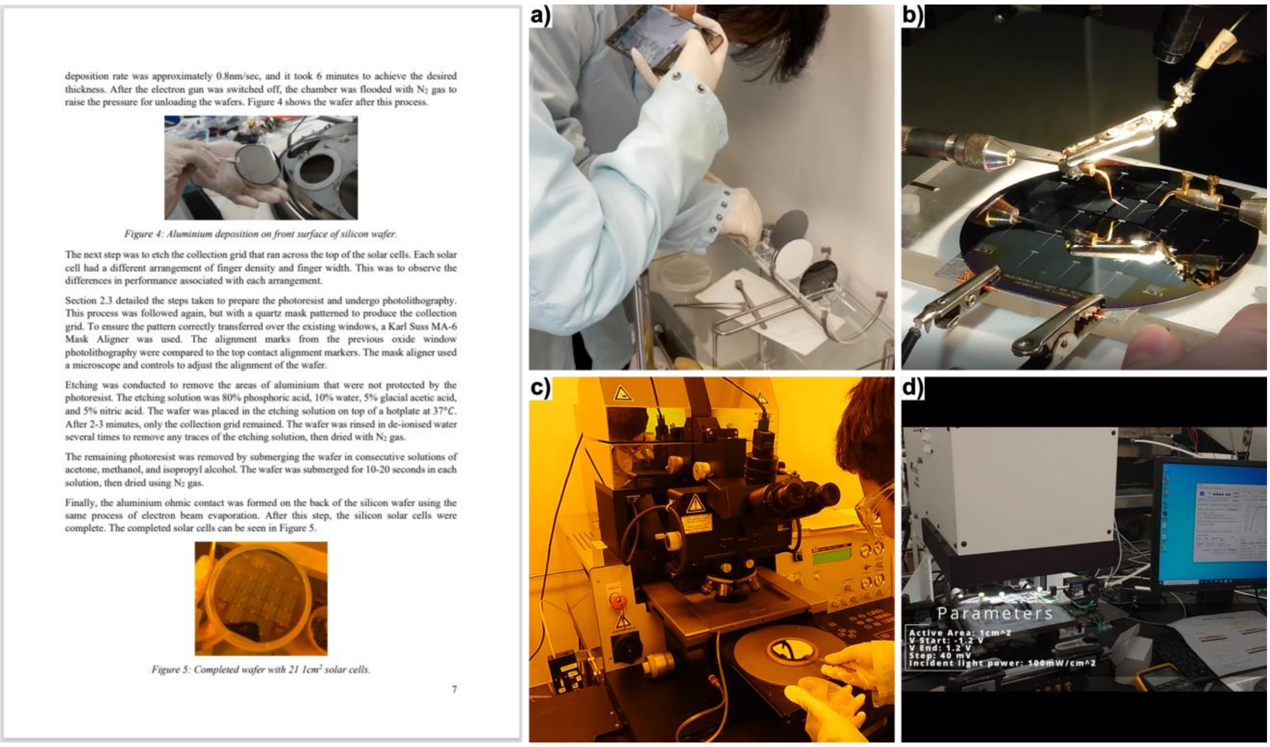


Figure 4 Left: A page in a student's submitted report as an example. Right: Photos of students working on different fabrication processes (a-c), and a screenshot of the video made during the lab for students who are unable to attend the lab demonstration (d).

Pre-COVID Arrangement

The Solar Cell Lab demonstration consists of four weeks of lab sessions with 2 to 3 streams of 2-hour lab sessions per week. Each session consists of 6 to 8 groups of students working in pairs. The first week is an overview of the Nanofabrication Laboratory at the University of Canterbury. During this session, tutors will assign cells to students and each pair will work on the same cell for the remainder of the session. In addition, tutors will introduce the main equipment available in the lab and explain the basic manufacturing processes involved in the equipment. During the second lab session, since the boron diffusion time required was 30 minutes, the TAs also looked at methods for determining the thickness of SiO_2. The third session is usually the busiest session of the solar cell lab, as each pair of students must complete several fabrication processes within the allocated 2 hours lab session. Additional helpers are often needed because the initially contracted TAs cannot attend all groups at once. Typically, each group of students is given about 5 minutes for each process for the lab to finish on time. Because of the number of students in each session, it is difficult to get everyone into the yellow room while still ensuring they have enough space to move between treatment stations. So, in addition to the TAs, the teaching staff also had to step in and accompany them, so that they did not sit in the lab for almost an hour doing nothing. Similarly, for the final practical session, since all the students had to go through four different characterisation techniques, each group of students had a maximum of 15 minutes for each characterisation station.

Post COVID

Because of the COVID-19 outbreaks in 2020 and 2021 and the New Zealand Government's implementation of a traffic light system in 2022 to cope with the impact of the Omicron virus while maintaining social dynamics, the restriction of the maximum number of people allowed in a room at any given time was implemented by the University based on the COVID response guidelines published by the Tertiary Education Commission (Taylor et al., 2024). In addition, the number of enrolments of ENEL 491 increased to nearly 60 students in 2022, and almost 70 students in 2024. This led to difficulties in maintaining only 3 lab streams as before the pandemic due to the confined space in the lab and the requirement of social spacing. To ensure students were approximately 1 m apart, we increased the number of streams to 12 over two weeks for the same lab session, reduced the number of students per session to 6 (3 pairs), and reduced the time allocation of each lab session to a maximum of one hour. The introductory lab in the first week is combined with the lab in the second week on impurity diffusion. This reduces the total number of required lab sessions to three instead of four, as before the outbreak. Moreover, we appointed one additional TA, grouped them into two groups, and assigned their lab demonstrations in alternate weeks to ensure at least one TA was available if the initially assigned TA tested positive with COVID. Table 1 and Table 2 compare the lab demonstration arrangements before and during the COVID-19 outbreak. In addition to in-person lab sessions, videos of the microfabrication process conducted during lab sessions were also recorded and uploaded to the UC Learn webpage. This allows unvaccinated students or students who were in quarantine due to a positive COVID test result to see what was done in lab sessions they missed and to catch up in the next class.

Table 1 Comparison of the lab hours before and during the COVID Outbreak, excluding the preparation time before and between lab sessions.

Based on 60 students	**Before COVID-19 Pandemic**	**During COVID-19 Pandemic**
# Streams	3	12
# Groups per Stream	10	3
Lab Hours per Stream per Week	2	1
Total Lab Weeks per student	4	3
Total TA Hours during Lab sessions	24	36
Total TA Lab Working Weeks	4	6

Table 2 Comparison of the lab schedule before the COVID-19 outbreak (left) and during COVID-19 Red-Alert-Omicron Phase 3 (right).

<table>
<tr><th colspan="2">Before COVID-19 Pandemic</th><th colspan="2">During COVID-19 Red Alert-Omicron Phase 3</th></tr>
<tr><td rowspan="2">Week1</td><td rowspan="2">Lab Introduction</td><td>Week1</td><td>Lab Introduction + Boron Diffusion (Stream A-F)</td></tr>
<tr><td>Week2</td><td>Lab Introduction + Boron Diffusion (Stream G-L)</td></tr>
<tr><td rowspan="2">Week2</td><td rowspan="2">Boron Diffusion</td><td>Week3</td><td>Top Metal Contact Patterning (Stream A-F)</td></tr>
<tr><td>Week4</td><td>Top Metal Contact Patterning (Stream G-L)</td></tr>
<tr><td rowspan="2">Week3</td><td rowspan="2">Top Metal Contact Patterning</td><td>Week5</td><td>Characterisation (Stream A-F)</td></tr>
<tr><td>Week6</td><td>Characterisation (Stream G-L)</td></tr>
<tr><td>Week4</td><td>Characterisation</td><td></td><td></td></tr>
</table>

Outcomes

After rearranging the lab, we observed that the students were more active in the lab sessions. This was not limited to questions students asked about the manufacturing process demonstrated in the lab or about graduate student life and the semiconductor manufacturing industry environment, but also included interactions between students. This was especially helpful for students returning from the lockdowns they experienced in 2020 and 2021. At the beginning of the lab sessions, some students who were about to complete their bachelor's degrees still needed to introduce themselves to each other.

During the impurity diffusion session, due to the required 30-minute diffusion time, the TAs often need to fill up the time by providing and explaining the fabrication parameters that the students need for solar cell characteristics calculation, as well as presenting their own research. This is usually not enough to cover the whole 30 minutes. To fill out the 30-minute waiting time, TAs also relied on students to ask questions regarding any of the information demonstrated by TAs. In the pre-pandemic setup, perhaps due to the number of students per stream (nearly 20), students were more reluctant to ask questions, even when TAs proactively encouraged them to ask questions relating to the topics that TAs demonstrated. In addition, most of the laboratory equipment was already introduced and explained during the first introductory lab session. This results in fewer teaching materials that TAs can demonstrate during the 30-minute diffusion wait. After the rearrangement, students are more proactively raising questions relating to the solar cell fabrications and the working principles of lab equipment that are not part of the solar cell fabrication processes.

From the TAs' perspective, although the increased number of streams meant they had to repeat the same demonstration multiple times, having only 3 groups per stream allowed them to take short breaks between classes. Before the labs were rearranged, TAs often had to work for 2 hours without any quick bathroom breaks. In addition, regardless of the amount of experience TAs had with the lab in previous years and the multiple times in reviewing the procedures, problems with broken wafers or chemicals and equipment not working as expected could still arise during lab sessions. This happened in the characterisation week when the solar cell dark IV measurement had contact issues. The TA was able to ask the students to move on to other characterisation stations and had around half an hour to solve the problem. However, TAs had less than 10 minutes to sort out the issue for the lab to finish on time with the pre-COVID setup. The need to resolve problems quickly leads to additional stress for TAs as they have no time to investigate before the next group arrives. Therefore, the students may be turned away and asked to return outside the originally scheduled lab time to complete the process. After the new arrangement, one TA can redirect the student to complete other testing stations first, while the TA resolves the issue during the lab session.

Before the new setup, additional help is required from the academic staff and other postgraduate students. For the top metal contact patterning, at least 6 teaching staff are needed to accommodate all students within one stream due to the multiple fabrication steps required. This can be reduced to 3 in total with the new arrangement. TAs can also have some breaks in between groups, allowing TAs to relax from stressful lab demonstrations.

When the student number was less than 35 before 2019, only two TAs were contracted for the main preparation and demonstrations. One TA would have had previous years of solar cell lab demonstration experiences, and the second one was usually new to the field with some CMOS fabrication experiences. The new TA, usually expected to have enough knowledge for lab demonstrations, was only shown once of the fabrication process before the lab commencement and would need to become the trainer for another new TA in the following year. It is sometimes a common issue that a new TA needs to ‘learn and teach’ simultaneously. The short training period before the lab demonstration could easily lead to TAs feeling stressed because they were not confident enough in the quality of lab teaching that they delivered. This could also hinder the quality of lab demonstrations provided by TAs (O'toole, 2012).

Before COVID, as the student number grew to almost 50, academic staff or lab managers could not overlook all groups since they also needed to jump in and help with part of the lab demonstration process. This leads to TAs with no one to ask when they are uncertain about the fabrication processes that they need to demonstrate or the questions from students that they cannot answer. With the rearrangement done in 2022, the lab manager can be freed from a single fabrication process station and focus on providing help when TAs needed, as well as providing active feedback to TAs on their demonstration methods between student groups. This helps build the TAs' competency through mentoring from lab managers or academic staff (O'toole, 2012).

The TAs appointed in 2022 were initially divided into two groups, one group that works in weeks 1, 3 and 5, and the other group that works in weeks 2, 4 and 6. This ensures that if one of the TAs tests positive for COVID-19, we have enough assistants to cover laboratory demonstrations. In the first lab session (week 2), an assistant had a conflict with other work and was unable to attend. This results in one TA short for the lab demonstration on week 2. A TA from week 1 was able to quickly come in and take over because he was on standby during lab week 2, 4, and 6. The flexibility in assigning TAs according to the actual needs during the lab demonstrations reduces the stress and additional work in finding extra TAs when the assigned TA is not available. This enables us to focus more on the lab demonstration itself.

In 2023, we made small adjustments to the arrangement by increasing the allocated time slot for each lab session to 90 minutes. The extra time allows better time flexibility for each fabrication or measurement process and ensures a proper break for TAs between streams if the lab streams are scheduled one after another without any breaks in between. It is also worth noting that we make minor adjustments to the solar cell lab structure each year based on the student number and the availability of TAs. The lab manager and the course coordinator also need to work closely with the university's timetabling team regarding the lab timetables. Given that final-year students usually have fewer lectures compared to first-year students and most courses are selective, so far we have no problem fitting all streams into the teaching weeks needed. In 2024, excluding students who were unwell and could not attend the lab, the student turnout rate for the lab reached 100%.

Conclusions

The Solar Cell Lab at Electrical and Computer Engineering, University is a crucial teaching module in the ENEL 491 Nano Engineered Device course that has been running for over a decade, offering students hands-on experience in semiconductor fabrication and device characterisation. With the assistance of experienced technical staff, students learn essential wafer and device processing skills. The number of students enrolled in the course has significantly increased, indicating a growing interest in semiconductor manufacturing and nanotechnology research. In response to the COVID-19 outbreak and the implementation of the traffic light system in New Zealand, the University restricted the maximum number of people allowed in a room. This led to challenges in maintaining lab sessions as before the pandemic, prompting the course coordinator to increase the number of lab streams and reduce the number of students per stream to ensure social distancing. In addition to in-person lab sessions, recordings of lab demonstrations were uploaded to the internet for unvaccinated students or those in quarantine to catch up on missed labs. After rearranging the lab, student engagement increased significantly. TAs also benefitted from the changes, as they had more manageable group sizes and could take short breaks between classes.

In 2023, further adjustments were made to allocate 90 minutes for each lab session, providing more flexibility and ensuring TAs had adequate breaks. By 2024, the student turnout rate for the lab has improved significantly, with a 100% attendance rate excluding students who were unwell and communicated before the commencement of the lab demonstration. The improvements in the lab setup demonstrated a positive impact on student engagement and overall efficiency in conducting lab sessions.

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