



Next-Generation Selective-Emitters for commercial PERC and TOPCon Solar Panels

Project Results and Lessons Learnt

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Table of Contents

Table of Contents..... 2

Executive Summary..... 3

Project Overview..... 4

 Project summary 4

 Project scope..... 4

 Outcomes..... 5

 Transferability 5

 Conclusion and next steps 5

 Lessons Learnt Report: Impact of Metal/Si Interface Areas on Solar Cell Performance 6

 Lessons Learnt Report: Contact formation between non-fire-through (NFT) Ag contacts and laser-doped silicon surface 9

Executive Summary

The main focus of the ARENA 2020/RND005 project is to research and develop novel laser-doped selective emitter (LDSE) and screen-printed contacting technologies for industrial silicon solar cells to address the fundamental limitations of highly recombination-active metal/Si interfaces on the efficiency of current screen-printed solar cells.

With over 97% of the market share in the current PV industry, screen printing has long been recognized as a robust and cost-effective technique for the metallization of silicon solar cells. Despite significant improvements in the performance of screen-printed contacts in solar cells, one remaining limiting factor to the efficiency of screen-printed industrial PERC and TOPCon solar cells is carrier recombination losses at metal/Si interfaces, which are becoming increasingly detrimental as the silicon bulk and surface passivation quality continuously improve in industrial solar cells. With current finger spacings of approximately 1.3 mm, the traditional contacting pattern design results in more than 5% metal/Si interface areas, limiting open-circuit voltage (V_{OC}) of industrial PERC solar cells to 680-690 mV and therefore efficiency. To allow further improvements in the efficiency of industrial screen-printed solar cells, overcoming such efficiency limitations from carrier recombination at metal/Si interfaces will be a critical requirement for the future developments of screen-printed solar cells in the PV industry.

This final report marks the completion of this project, which has successfully developed several novel LDSE technologies and contacting technologies to mitigate contact recombination losses in screen-printed solar cells with greatly reduced metal/Si interface areas. With detailed numerical simulation studies, we have established reducing metal/Si interface areas as an effective approach to significantly lower contact recombination losses and improve the efficiency of screen-printed PERC solar cells, which has also been identified as a critical component in the efficiency roadmap towards 24% efficiency for industrial screen-printed PERC solar cells. Subsequently, two novel contact schemes, namely 'low-area laser-doped contacts' and 'low-area selective contacts', have been developed and evaluated in this project. Both designs are capable of achieving ultra-low metal/Si interface areas of less than 0.5% of the total cell area while still maintaining their compatibility with industrial standard screen printers with sufficient alignment tolerance enabled. With the developed contacting technology, we have demonstrated up to 12 mV improvements in V_{OC} and more than 0.3%_{abs} gains in the efficiency of PERC solar cells compared to conventional contacting design. Furthermore, a batch of full-area bi-facial PERC solar cells have been successfully fabricated at partners' production facilities, with a promising peak efficiency of 23.71%_{abs} achieved.

Overall, the project has met all its milestones. The developed novel contacting technologies are of significant importance for unleashing the full efficiency potential of screen-printed solar cells and providing cheaper electrical power from PV technologies.

Project Overview

Project summary

The purpose of this project was to develop new LDSEs and contacting technologies to address key limitations of carrier recombination losses at metal/Si interfaces on the efficiency of screen-printed industrial silicon solar cells.

The first phase of this project was related to the fundamental development of the low-area screen-printed contacts and focused on understanding the key effects of the technologies on recombination mechanisms affecting solar cell performance. In particular, it has addressed the key potential challenges faced by the proposed technologies, including the effectiveness of doping, contact resistivity, recombination in exposed/metallized regions, bulk defect generation and deactivation of defects. Detailed numerical simulation studies have also been conducted with Sentaurus and Quokka to ensure technology viability and determine the efficiency potential of proposed technologies. The simulation results also led to an optimization of the contact geometries and the identification of key technical requirements for these technologies.

In the second phase of the project, the proposed contacting technologies were experimentally validated with the fabrication of finished PERC solar cells in the laboratory, using partially processed precursor samples from partners Trina and Talesun. The key focus of this phase was to identify any challenges related to the fabrication process and to optimize the overall contacting pattern design. One particular issue identified for the low-area laser-doped contacts was the high contact resistivity between non-fire-through (NFT) silver (Ag) contacts and laser-doped silicon surface, which strongly limited the fill factor and the efficiency of solar cells fabricated with such contact structure. The root cause of this issue can be largely attributed to the lack of Ag crystallites formed at the silicon surface as a result of the low reactivity of the glass frit system used in NFT Ag pastes. This unexpected finding will encourage more developments of NFT Ag pastes in the future, which could advantageously expand their applications in the PV industry. In the meantime, a promising V_{oc} gain of 12 mV and efficiency improvements of up to 0.3%_{abs} have been demonstrated on PERC solar cells fabricated with the low-area selective contact design, compared to reference cells with conventional screen-printed contacts.

In the third phase of the project, pilot testing of production (full-area finished PERC solar cells) has been carried out in SIRF and partner facilities, with ongoing cell optimization and loss analysis and module fabrication. By optimizing the contacting pattern design and paste chemistries and overcoming several processing issues encountered throughout in-house fabrication at UNSW, a batch of large-area bi-facial PERC solar cells have been successfully manufactured at partner facilities with a remarkable average efficiency above 23.60%_{abs} and a peak efficiency as high as 23.71%_{abs}.

Project scope

The overall objective of the project is to reduce the overall manufacturing cost (\$/W) and the levelized cost of electricity (LCOE) for PERC and TOPCon panels. This was achieved by developing a next-generation low-area LDSE screen-printing technology for PERC and TOPCon solar cells that is

compatible with screen-printing to address performance-limiting front emitter/metal recombination. This is expected to be a critical step to enable efficiencies of over 24% for PERC solar cell technology with minimal added Capex and processing costs.

Outcomes

The following outcomes have been achieved in this project:

1. Demonstration of a pathway to take industrial screen-printed PERC solar cells to >24% efficiency, and >24.5% for LDSE TOPCon solar cells while avoiding the need to transition to alternative metallization schemes like plating.
2. Develop a low contact area screen-printed contacting scheme to address the performance limiting factor for industrial PERC and TOPCon solar cells – namely emitter and metal/Si interface recombination on the front surface. The project will develop an LDSE technology for both PERC and TOPCon with <2% laser doping area and <1% metal/Si interface area, which is compatible with a screen-printing alignment tolerance of +/- 30 microns, with minimal processing changes and Capex investment.
3. Gain a fundamental understanding of the contact resistance achievable with screen printing on laser-doped regions, J_0 values of exposed laser-doped regions and impact of metal/Si interface contact area and the adhesion of floating screen-printed contacts.

Transferability

The low-area laser-doped screen-printed contact scheme developed in this project was designed to be compatible with the industrial screen-printing process, where reductions in metal/Si interface areas were achieved in a way that reductions in printed width of fingers are not required, and sufficient alignment tolerance can also be provided with the unique dash or wavy geometries. This will ensure good compatibility with mass production and relatively smooth technology transfer from the lab to the industrial environment. The transferability was further validated by the small-batch pilot production at partner facilities using industry-standard equipment. In addition, the cost analysis results extended the benefits for the developed technology from improving efficiency to significantly reduced manufacturing costs and LCOE. Such cost benefits could also provide great incentives for the commercialization and adaptation of these technologies in the PV industry.

Conclusion and next steps

The successful completion of the third and final phase of the project marks the achievement of all key milestones and expected outcomes. The developments and demonstration of novel contacting technologies to address fundamental performance limitations of screen-printed contacts provide a promising pathway to improve efficiency and reduce the costs of silicon solar cell technologies. In addition, the identification and investigation of several challenges encountered throughout the project, such as high contact resistivity between NFT Ag contacts and laser-doped silicon surface, has highlighted the need for continued research and optimizations into the properties of screen-printing pastes. With promising results from pilot production testing, the commercialization and further optimizations of our developed technologies for mass production will continue in future projects.

Lessons Learnt Report: Impact of Metal/Si Interface Areas on Solar Cell Performance

Project Name: Next-generation selective-emitters and selective-contacts for commercial PERC and TOPCon solar panels (R&D project)

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

A key aspect of this project has been the development of novel contacting designs for screen-printed PERC solar cells with significantly reduced metal/Si interface areas to mitigate contact recombination losses at metal/Si interfaces. Throughout this, we have demonstrated the detrimental impact of front-side metal/Si interface areas on open-circuit voltage of PERC solar cells (see **Fig.1**), where solar cells with larger metal/Si interface areas suffer from significantly more contact recombination losses and hence have substantially lower open-circuit voltage and efficiency. With that in mind, reducing the metal/Si interface area can provide an effective way to improve the efficiency of screen-printed solar cells by mitigating contact recombination losses. However, it must be noted that reductions in metal/Si interfaces area could also lead to increases in resistive losses (see **Fig.1**) due to elevated contact resistance and the potential introduction of additional spreading resistance in localized contact regions (see **Fig.2**). This presents a clear trade-off between contact recombination losses and resistive losses in contacting pattern designs.

Implications for future Projects

In future projects, a systemic approach shall be taken for any modifications and optimizations of contacting pattern designs to take into account the impact of power losses from different mechanisms. For instance, reducing metal/Si interface areas to lower contact recombination losses in screen-printed solar cells must be done in a way without triggering excessive increases in resistive losses, which requires careful evaluation to balance reductions in contact recombination losses and increases in resistive losses. Furthermore, increases in contact resistive losses can be largely avoided if much lower contact resistivity can be achieved at metal/Si interfaces. With lower contact resistivity, significant improvements in efficiency especially for solar cells with a greatly reduced metal/Si interface area can be expected. This presents a promising research opportunity for the future development and optimization of screen-printing paste properties and LDSE technologies in future project.

Knowledge gap

It has been shown that the performance of solar cells with the proposed low-area screen-printed contacts will greatly benefit from reduced contact resistivity. However, a key knowledge gap identified is how to achieve a lower contact resistivity without deviating from the current LDSE technology and the use of industrial standard Ag pastes. On the one hand, it is possible that the reactivity of the glass frit system used in current Ag pastes needs to be improved to enhance the formation of Ag crystallites on the silicon surface. On the other hand, a modified laser doping

process to form more heavily doped LDSE regions might help reduce the barrier height at metal-semiconduction interfaces to achieve a lower contact resistivity. However, the formation of a more heavily doped LDSE silicon surface will likely lead to increases in surface and Auger recombination losses in such regions, which subsequently requires further reductions in the coverage area of laser-doped regions to avoid excessive recombination losses. These possible approaches warrant further investigation in future projects.

Background

Objectives or Project requirements

The aim of this part of the project was to identify and experimentally validate approaches to significantly reduce carrier recombination losses at metal/Si interfaces in silicon solar cells without transition to alternative metallization technologies, such as plating.

Process undertaken

Finished PERC solar cells and testing structures utilizing the proposed contacting technologies with different metal/Si interface areas in the range between 0.5-2.0% of the total cell area have been fabricated at UNSW using partially processed PERC solar cell precursors provided by partners of this project. To evaluate the impact of metal/Si interface areas on recombination and contact resistive losses, PL and EL imaging was performed on those samples. Furthermore, the contact resistance/resistivity of contacts with different metal/Si interface areas was characterized by the transfer length method. Due to difficulties in separating the spreading resistance from measured contact resistance in TLM measurement, the impact of the spreading resistance at localized metal/Si interfaces was simulated using Quokka 3.

Supporting information (optional)

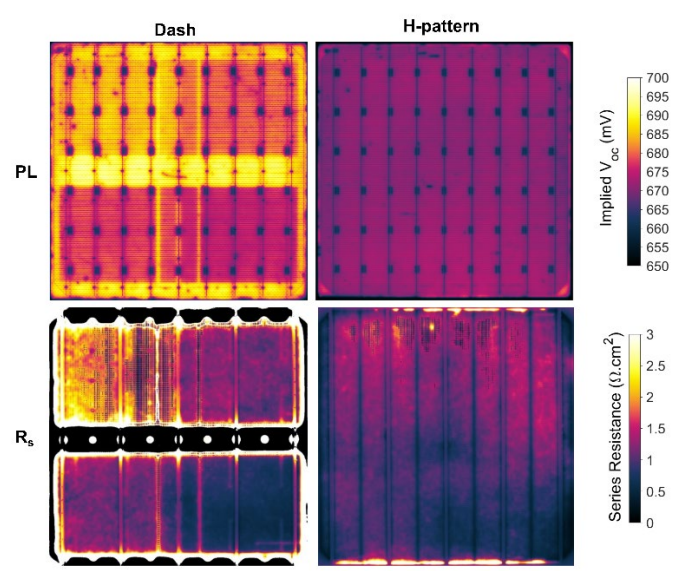


Figure 1. Photoluminescence (top) and series-resistance mapping (bottom) images of PERC solar cells fabricated with (left) low-area selective contacts and (right) conventional H-pattern contacting grids. The metal/Si interface area with conventional H-pattern grids is 4-5%. The metal/Si interface area with the proposed low-area selective contact is 0.5, 1.0, 1.5, 2.0% from the top left quadrant to the bottom right quadrant.

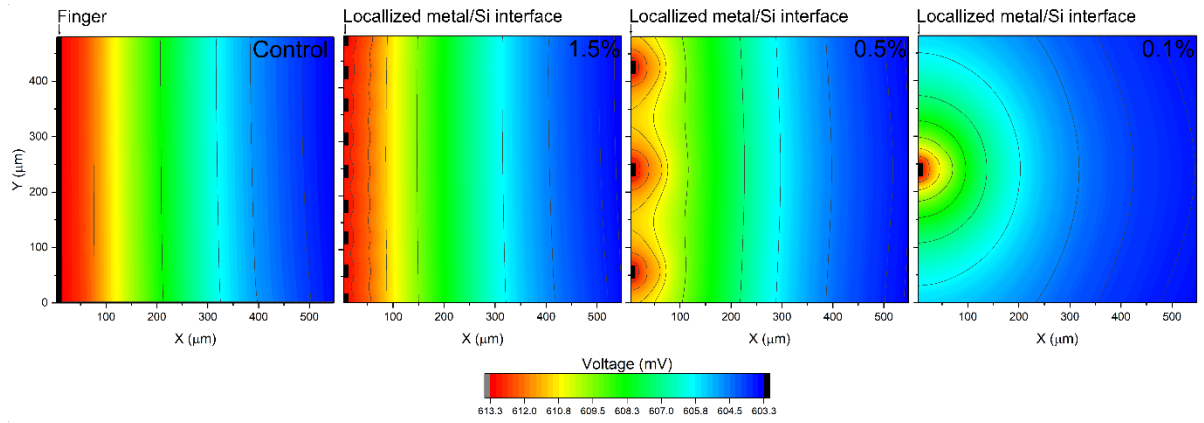


Figure 2. Contour plots of the surface potential near contact regions with conventional continuous finger design and localized metal/Si interface with reduced coverage areas.

Lessons Learnt Report: Contact formation between non-fire-through (NFT) Ag contacts and laser-doped silicon surface

Project Name: Next-generation selective-emitters and selective-contacts for commercial PERC and TOPCon solar panels (R&D project)

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

In order to reduce front contact recombination losses in screen-printed PERC solar cells, a novel contacting scheme was developed in this project based on the concept of low-area laser-doped contacts. Utilizing an alternative laser-doping technology in conjunction with the non-fire-through (NFT) floating silver (Ag) contacts, the formation of direct metal/Si interfaces is confined to regions where laser-doped lines and screen-printed NFT Ag contacts intersect. This can substantially reduce the front metal/Si interface areas in screen-printed PERC solar cells to less than 1% of the total cell area independent of the finger width that can be achieved with an industrial screen printer while still enabling sufficient alignment tolerance between laser-doped regions and screen-printed fingers. Microscopy images of the proposed low-area laser-doped contacts are shown in **Fig.3**.

Notably, due to reduced metal/Si interface areas, the achieving of a low contact resistivity between NFT Ag contacts and the laser-doped silicon surface is essential to ensure overall low power losses from contact resistance. However, forming metal/Si interfaces with NFT Ag pastes represents an unconventional use of NFT Ag pastes and has yet to be proved feasible, of which current industrial NFT Ag pastes are originally designed to form floating busbars without any requirements of contact formation. Followed by extensive investigation, forming high-quality ohmic contacts between NFT Ag contacts and laser-doped silicon surface proved to be one of the biggest challenges for the proposed low-area laser-doped contact design.

Despite this unexpected and frustrating roadblock to the development of low-area laser-doped contacts, determining the root cause of the contact formation issue with NFT Ag pastes on the laser-doped surface was still seen as a valuable research opportunity to broaden our knowledge and provide insight into the future development of such technology. It was found that a substantially reduced contact resistivity of only $0.5 \text{ m}\Omega\cdot\text{cm}^2$ can be achieved with conventional FT Ag pastes on the same laser-doped silicon surface, compared to $5\text{-}10 \text{ m}\Omega\cdot\text{cm}^2$ on the non-laser-doped surface or $1\text{-}5 \text{ m}\Omega\cdot\text{cm}^2$ on industrial standard LDSEs (see **Fig.4**). This suggests: (a) the contact formation issue for NFT Ag contacts cannot be attributed to the modified laser-doping process despite the heavily affected morphology of the silicon surface and the presence of crystallographic defects in laser-doped regions, and (b) the formation of heavily doped laser-doped regions with the modified laser-doping process can result in significant benefits of improved contact quality, predominately due to high surface dopant concentrations.

To further evaluate the contact formation mechanisms of NFT Ag contacts, scanning electron microscope (SEM) analysis and energy-dispersive X-ray spectroscopy (EDS) analysis were performed at interfaces between NFT Ag contacts and the silicon surface. Compared to conventional FT Ag contacts, a substantially reduced number of Ag crystallites were observed at metal/Si interfaces with NFT Ag pastes (see **Fig.6**), where the lack of effective formation of Ag crystallites on the silicon surface can be considered one of the most fundamental reasons for the contact formation issues of NFT Ag pastes. Given that the formation of Ag crystallites on the silicon surface is closely related to the direct reaction between Ag^+ ions dissolved in the glass layer and the silicon surface, such a low

density of Ag crystallites formed with NFT Ag pastes could be largely attributed to the special glass frit system of them. On the one hand, the very thin glass layers observed in SEM images (see **Fig.5**) suggest that the amount of glass layer participating in the reaction responsible for Ag crystallite formation could be inherently low for NFT Ag pastes. On the other hand, to avoid significant penetration through SiN_x during the firing, the glass system used in NFT Ag pastes should have substantially lower reactivity with both SiN_x and the silicon surface, which could lead to the ineffective formation of Ag crystallites with such pastes.

Implications for future Projects

Despite unexpected challenges to the development of low-area laser-doped contacts in this project, the identification and understanding of the root cause of the high contact resistivity between NFT Ag contacts and silicon surface will continue to be relevant and valuable for future developments of novel contacting designs. For current standard NFT Ag pastes available in the PV industry, their application could be extended well beyond forming floating busbars only, providing the contact formation properties can be significantly improved without affecting the fire-through behaviour. This will present exciting opportunities for developing a wide range of contacting pattern designs utilizing such paste materials.

Knowledge gap

The special glass frit system used in industrial NFT Ag pastes has been identified as the root cause of the contact formation issue of NFT Ag pastes encountered in this project. Although it is very like that a more reactive glass frit system is required to improve the Ag crystallite formation and achieve a low contact resistivity with NFT Ag pastes, a key knowledge gap is that if such NFT Ag pastes can remain floating without penetrating through SiN_x layers during the high-temperature firing especially given that the fire-through properties could also be enhanced with the use of a more reactive glass frit system. It is more desirable that such modifications in NFT Ag paste chemistry can selectively improve its reactivity with the silicon surface without affecting the etching behaviour and the reactivity with SiN_x layers. To bridge this knowledge gap, further paste developments and investigation are required in future projects.

Background

Objectives or Project requirements

This phase of the project aims to develop a novel low-area laser-doped contact scheme utilizing a modified laser-doping process and NFT Ag pastes to greatly reduce the front-side metal/Si interface areas in screen-printed PERC solar cells.

Process undertaken

Laser doping was performed using a continuous-wave (CW) 532 nm Newport/Spectra-Physics Millennia Prime Pump Laser with a gaussian beam shaper. To form the heavily doped n-type LDSE regions, 85%_{v/v} phosphoric acid (H_3PO_4) was spun as a dopant source onto the front side of partially processed PERC cell precursors provided by the partner prior to laser doping. Full-area laser-doped boxes consisting of overlapping lines were created on the sample surface using various combinations of the set laser power in the range of 10-25 W and set laser speeds between 0.5 and 12 m/s. Subsequently, metal fingers were printed on laser-doped regions using an industrial screen printer with both FT and NFT Ag pastes sourced from an industrial supplier. All samples were fired using an industrial belt furnace at a peak temperature of 780 °C.

To determine the contact resistivity, all samples were laser cleaved from the back side into 5 mm-wide stripes prior to the transfer length measurement. To further investigate the microstructural properties of NFT and FT Ag contacts, a two-step selective etching process was carried out, including 30 mins etching in 70% HNO_3 at 65 °C to remove the bulk silver of screen-printed fingers and expose underneath glass layers, followed by 1 min HF dip to remove glass layers and reveal any Ag crystallites formed at the silicon surface. The physical and chemical properties of such microstructures were analyzed with SEM and EDS.

Supporting information (optional)

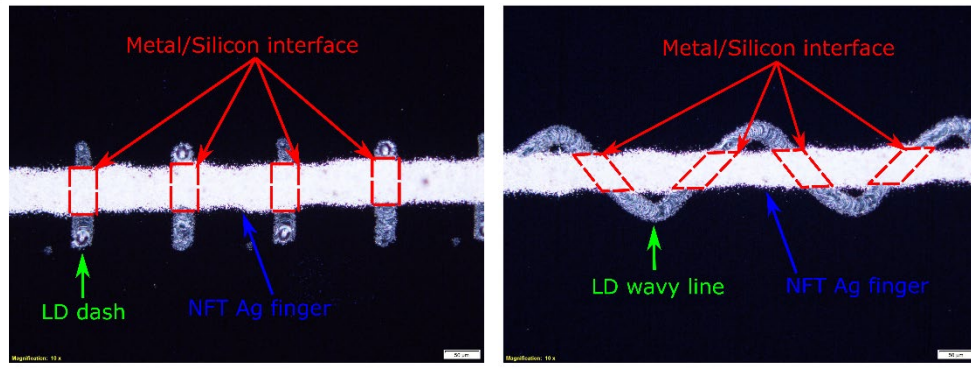


Figure 3. Microscopy images of low-area laser-doped contacts with laser-doped (left) dash lines and (right) wavy lines.

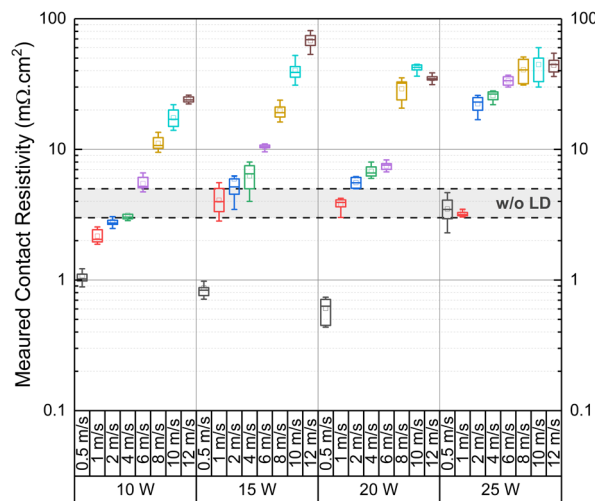


Figure 4. Measured contact resistivity of FT Ag contacts on laser-doped silicon surface with different laser conditions.

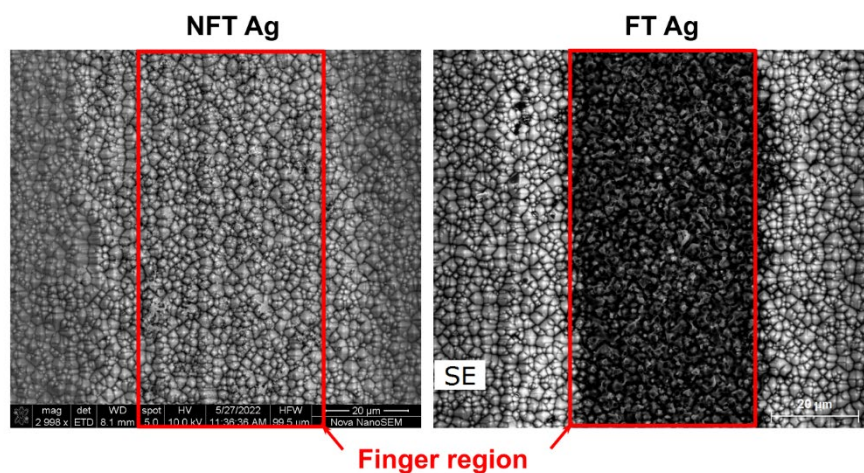


Figure 5. Scanning electron microscope images of (left) NFT and (right) FT Ag fingers after etching off bulk silver.

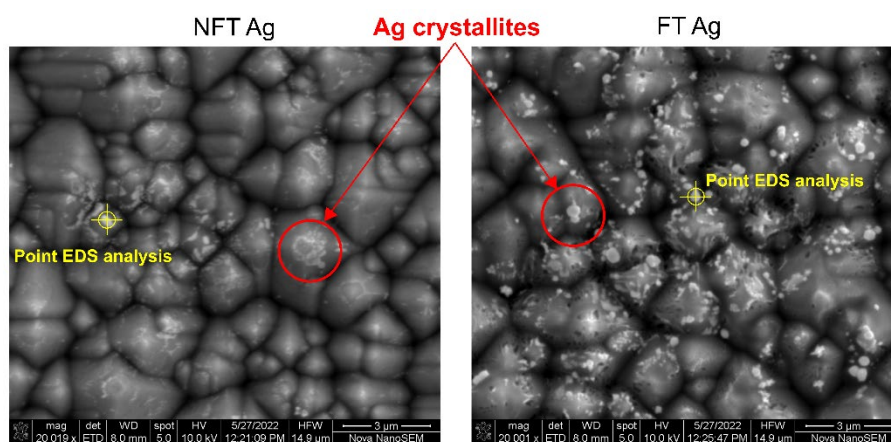


Figure 6. Scanning electron microscope images of NFT (left) and FT (right) Ag fingers after etching off bulk silver and glass layers.