Local doping using Laser Chemical Processing technology for advanced silicon solar cells - Project results and lessons learnt

Lead organisation:	The Australian National University
Project commencement date: 1/04/2013	**Completion date:** 31/03/2015
Date published:	
Contact name:	Klaus Weber
Title:	Associate Professor
Email: klaus.weber@anu.edu.au	**Phone:** 6125 0734
Website:	https://cecs.anu.edu.au/

Please use plain English – no jargon or unnecessary technical terms

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Executive Summary

Laser processing can be used in various ways as part of the solar cell manufacturing sequence. There exists an opportunity to improve existing manufacturing lines through the incorporation of laser processing, which can simplify the manufacturing process and allow an increase in solar cell conversion efficiency. However, industrial implementation requires that the laser processes are very well understood and optimised. This has proved difficult to do in the past, as it is quite time consuming to obtain reliable information on the properties of laser processed regions.

The aim of this project was to develop new techniques that would allow the fast and accurate determination of the properties of laser processed regions. In this way, the laser processes can be quickly optimised, and the conversion efficiency of solar cells that could be achieved from the new process can be accurately predicted.

We achieved the project goals by developing two measurement techniques as well as a new computer model that together allow a comprehensive determination of the properties of laser processed regions. We have demonstrated the advantages of these techniques over the state of the art prior to the commencement of this project. These techniques allowed new insights and a better understanding of what happens during laser processing. The improved understanding will guide the development of further laser processes.

To demonstrate the usefulness of the techniques developed, they were used to optimise two quite new and relatively unexplored laser processes. We were able to demonstrate that both approaches allow high solar cell efficiencies to be realised. Solar cells fabricated with one of these approaches achieved efficiencies of nearly 21%, significantly higher than most commercially made solar cells.

Project Overview

Project summary

The aim of this project was to develop innovative measurement techniques for laser doped samples that can allow high quality data to be collected relatively quickly and accurately. Such techniques would then allow a more rapid optimisation of laser doping. By combining these techniques with each other and with suitable computer models, and cross –checking the results, a powerful and reliable measurement 'toolbox' for laser doping was to be developed and demonstrated.

We developed two measurement techniques; one of which uses a scanning electron microscope, while the other is based on the measurement of the light signal (so-called photoluminescence signal) given off by solar cells or test samples under operation.

Project scope

High Efficiency silicon solar cells – used to make the next generation of Photovoltaic panels – require relatively complicated structures. A typical structure is shown below. A key feature is that the rear contacts are localised and do not cover the entire rear surface, and that the silicon properties underneath the rear electrical contacts have been modified by introducing a high concentration of suitable 'dopant' atoms. These dopant atoms modify the electrical properties of the contact regions, leading to better electrical contacts and lower losses. Of the possible options available for the creation of such regions, the use of lasers, together with suitable dopant sources, is possibly the most promising avenue towards very high efficiency, low cost solar cells.

The process of laser 'doping' – the deliberate introduction of dopant atoms - involves shining a beam of laser light on the silicon solar cell being processed. The silicon illuminated by the light beam – which is typically 30 micrometers in diameter, less than the width of a human hair – absorbs the light and becomes sufficiently hot that it melts. When a material containing dopant atoms is present on top of the silicon, the dopant atoms become incorporated into the molten silicon. Once the laser light beam is turned off, the silicon solidifies again. The whole process typically takes less then one millionth of a second, so only the material directly in the path of the laser beam is modified.

Laser doping is a complex process that has proved difficult to understand and master. A prerequisite for process optimization is the accurate determination of the influence of those process variables critically affecting the solar cell energy conversion efficiency. An example of such a process variable is the laser power, which influences how much dopant is incorporated and how large the contact regions will be. Because laser doped regions are highly nonuniform over short distances, many conventional measurement techniques cannot be used, and alternatives must be developed.

This project focussed on developing innovative measurement techniques that can allow high quality data to be collected quickly and accurately, allowing a more rapid optimisation of laser doping. By combining these techniques, a powerful and reliable measurement 'toolbox' for laser doping was to be developed. The usefulness of this toolbox was then to be demonstrated by applying it to the

development of new laser processes and demonstrating improved solar cell energy conversion efficiencies.
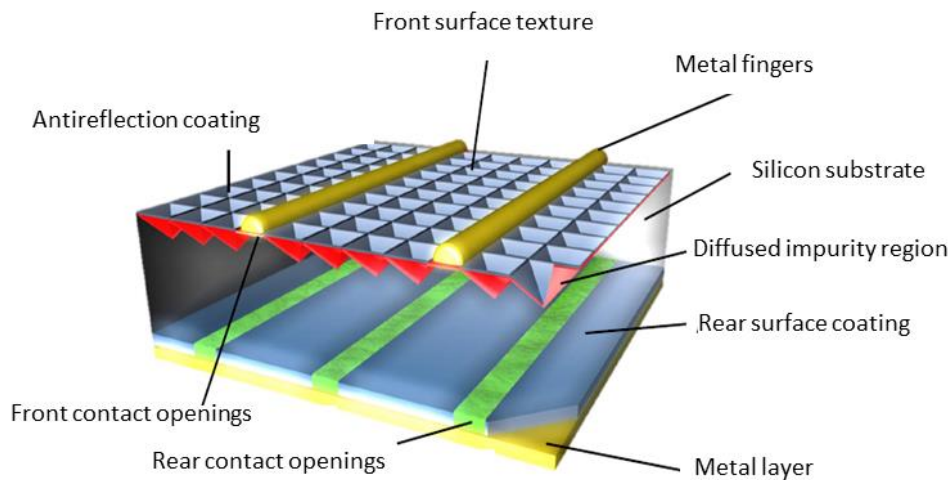

Figure 1: *An illustration of a typical high efficiency solar cell structure*

Outcomes

Dopant Imaging

One very important property of laser doped regions is the distribution of the incorporated dopant atoms around the laser 'spot' – the region where the laser beam was incident on the silicon solar cell and melted the silicon. Existing techniques to measure this distribution are complex, expensive and yield limited information. Relatively recently, researchers have discovered that, under certain circumstances, images from a scanning electron microscope can show contrast that is due to doping. This technique had never been applied to the assessment of laser doping. We were able to show that the technique can give detailed information about laser doped regions, and indeed can be used, in certain situations, to produce dopant concentration 'maps'. We studied laser doped regions in detail and determined the capabilities and limitations of the technique, as well as the most suitable microscope settings for obtaining high quality images. An example is shown below.

This information allows an assessment of the quality of the laser doped regions – how good an electrical contact can be formed to them, and whether the contact is likely to lead to additional losses in the solar cell. The technique is much simpler and cheaper than alternative techniques, and gives more information. It is a valuable new tool for the development of laser doping.
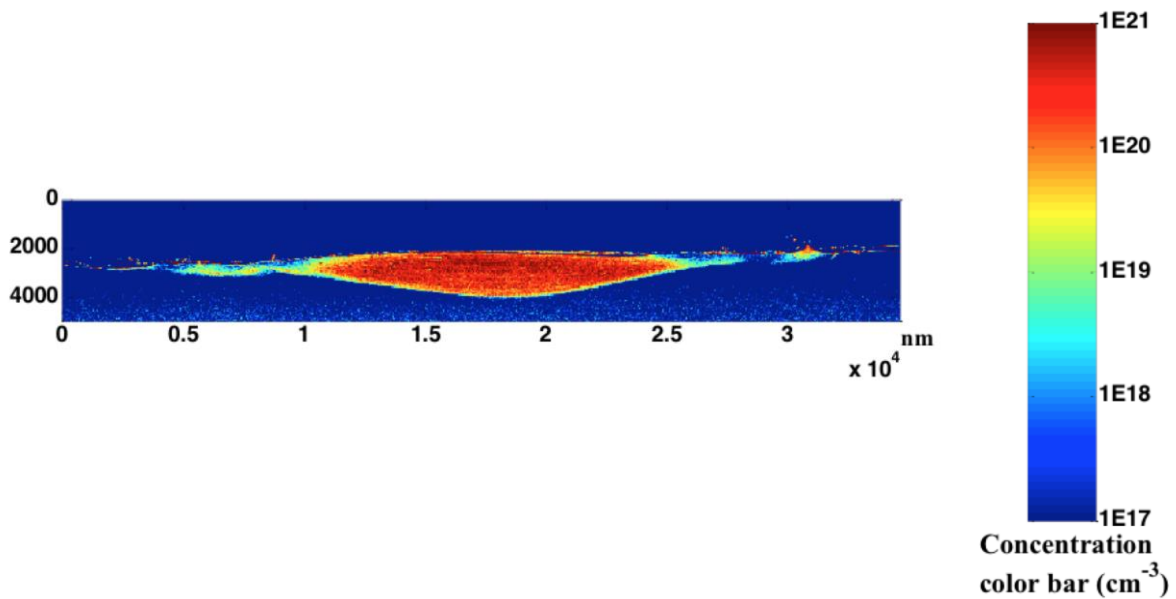
Figure 2: *False colour electron microscope image showing the cross section of a laser doped region. The region is about 30,000 nanometres, or 30 micrometers, in width and up to about 2,000 nanometres in depth. Red regions have the highest concentration of dopant atoms (up to 10^{21} per cubic centimetre) as per the concentration colour bar.*
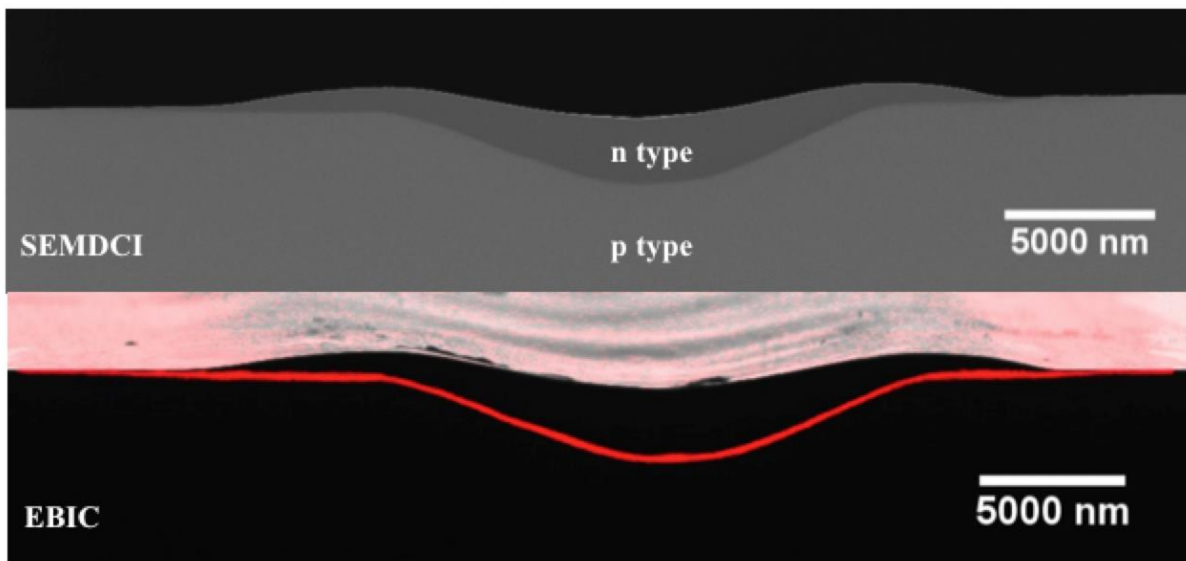

Figure 3: *Comparison of the same laser doped cross section analysed with electron microscope imaging technique (top image) and another, frequently used technique (electron beam induced current or EBIC, bottom image). The EBIC image only shows the edge of the laser doped region, which is visible as a bright red line. The electron microscope image gives information in the whole laser doped region, and in this case shows quite uniform doping.*

Assessment of the electronic quality of laser doped regions

Even if laser doped regions have a suitable doping profile and suitable dopant concentration levels, the electronic properties of these regions can vary dramatically. If the electronic properties are poor, it will not be possible to fabricate highly efficiency solar cells. The electronic properties are

dependent on the concentration and type of crystal defects that may be created during the laser doping process, as such defects can degrade the electronic quality. It is desirable to directly measure the electronic properties of laser doped spots and lines that may be used in solar cells. However, traditional techniques cannot accurately determine these properties. What is more, traditional techniques require large area samples for measurement, meaning that it is difficult to test many combinations of process variables in a short amount of time.

In operation, solar cells do not just absorb sunlight and convert it to electricity; they actually emit some light as well. This emission of light is called photoluminescence. The photoluminescence signal contains information on the electronic properties of the emitting sample. We have developed a sophisticated technique that combines photoluminescence images with computer modelling to allow the fast and very accurate determination of the electronic properties of the laser doped regions. The important features of our approach are:

- Only small areas are required for each set of process variables, so many process variables can be tested and measured on a single sample.

- The computer model (called Quokka) is much faster than other, existing computer models, but just as accurate. Further, other computer models are commercial packages that require expensive software licenses, while our computer model has been made freely available.

- The computer model also allows the accurate prediction of the efficiency of solar cells fabricated using a particular combination of process variables (using the electronic properties determined from the measurements). This makes it easy to determine which process variables are suitable to realise improvements in efficiency compared to current fabrication processes.

These features mean that it is possible, for the first time, to accurately and quickly determine the electronic properties of laser doped regions.
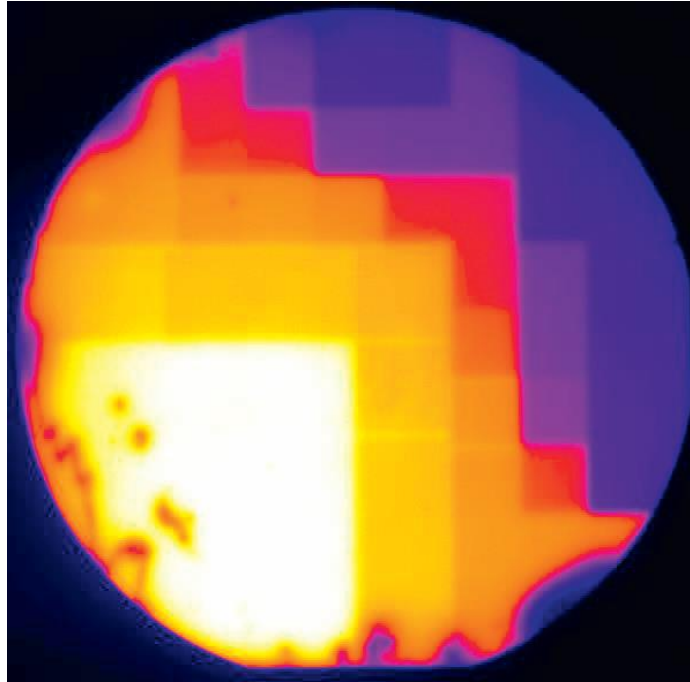
Figure 4: *Photoluminescence image of a 100mm diameter silicon wafer after laser doping. Each square-shaped area corresponds to a different combination of process variables. In total, 35 different combinations of process variables were trialled on the one wafer. Data from the photoluminescence image is then fed into the computer model that automatically determines the electronic properties for each combination of variables.*

Development and demonstration of new laser doping techniques

Two new laser doping techniques were further developed in this project, through application of the measurement techniques described above. One of these techniques consists of the application of a thin film of alumina (Aluminium oxide, Al_2O_3) and silicon nitride on the rear side of the solar cell. The alumina film is in contact with the silicon surface and improves the electronic properties of the surface. In addition, the alumina film contains aluminium, which is a suitable dopant for high efficiency solar cells. When the rear surface of the solar cells, with the alumina and silicon nitride films on the surface, is processed with a laser, the aluminium is incorporated into the silicon as a dopant. In this way, it is possible to use one material – alumina – to both protect the rear surface and to act as the doping source. This results in a very elegant and simple process for solar cell fabrication.

We fabricated solar cells with this approach, carefully optimising the process variables using the tools developed in the project. This allowed us to quickly reach solar cell efficiencies above 20% - above the efficiency of many commercially made solar cells. This efficiency can be further increased with some further process refinements. These promising new processes are being further developed for use in future generation solar cells.
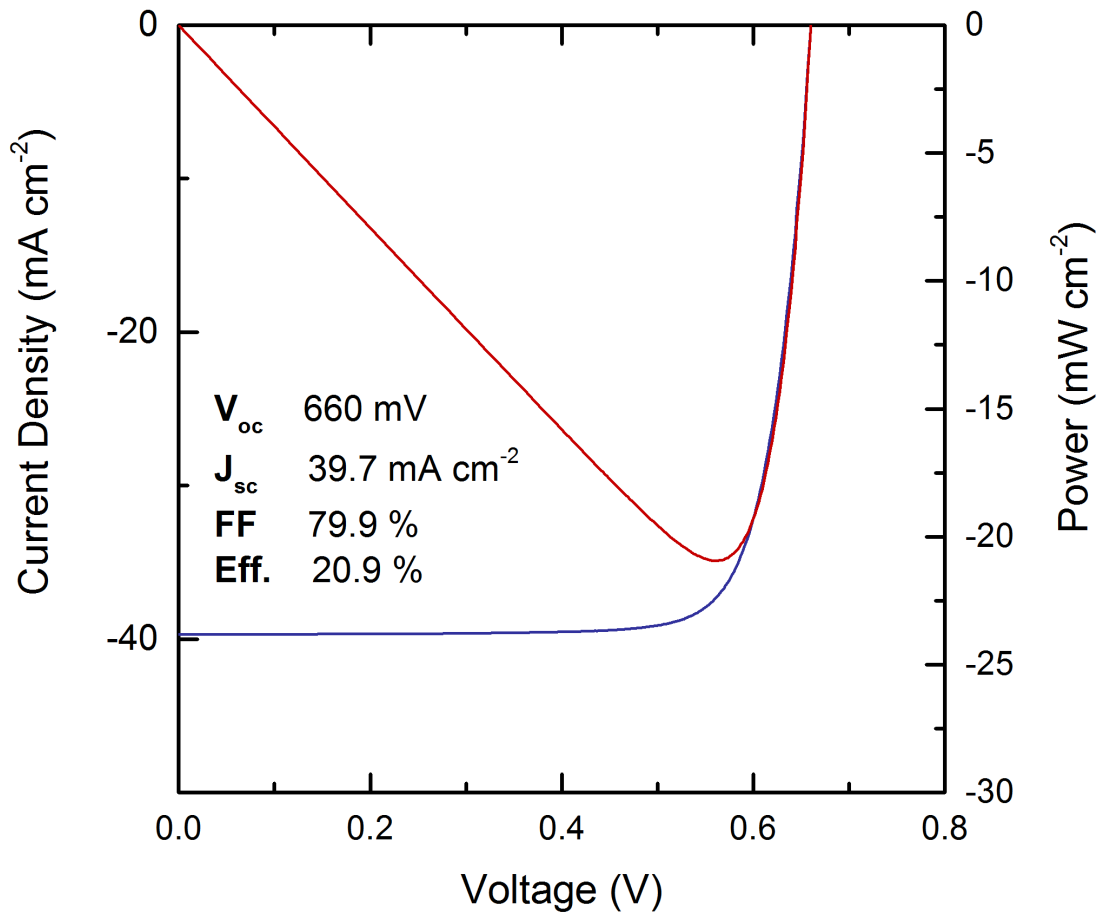
Figure 5: The current-voltage (blue) and power-voltage (red) curves of the 'champion' small area solar cell fabricated in this project. The cell displayed excellent characteristics and an efficiency of nearly 21%, above the efficiency of most commercial solar cells currently being manufactured.

These results mean that the project aims have been achieved, which represents a significant step towards more the more widespread commercial use of laser doping for solar cell manufacture.

Transferability

The techniques developed in this project have broad applicability for photovoltaics research and manufacturing. Quokka is freely available and broadly applicable to the analysis, simulation and optimisation of a wide range of solar cell structures, not just laser doped regions. The dopant imaging can also be applied to the analysis of heavily doped regions generally, and is not limited to doped regions formed using lasers. The laser doping technique based on the use of a thin Al_2O_3 film is likely to be developed further, and has received considerable attention in the wider research community.

Knowledge acquired during this project is being shared through publication of all the main results in scientific journals and presentation at scientific and technical conferences. In this way, the knowledge is effectively disseminated to potential users, namely researchers and engineers in

academia and industry. The Quokka software is freely available from the PV Lighthouse website www.pvlighthouse.com.au.

Conclusion and next steps

The successful project outcomes meant that the techniques developed and demonstrated are ready to be applied to further projects in research and industry. In fact, this is already the case, with all the techniques used by various research groups who are working on specific new technologies, aimed at further improving solar cell performance and reducing cost. Quokka in particular is extensively employed by research organisations (and increasingly solar manufacturers) to improve their technologies. In this way, the project outcomes are helping to drive down the cost of solar modules, and contributing to making solar electricity more affordable. This, in turn, will help to increase the uptake of photovoltaics, thus accelerating the shift to a renewable energy economy.

As an example, a current ARENA funded project between ANU, the University of NSW and Trina Solar – a top 3 solar PV manufacturer – aims to improve Trina Solar's solar cell technology in several important areas. Several of the project outcomes are being extensively used in that project, to help deliver the project goals and ensure further solar cell cost reductions at Trina.

[Guidance: Please use one template per each major lesson learnt and include as many as are relevant for your project. If what you learnt is more technical, this is the section to include technical information. However, please try to only use jargon when absolutely necessary!]

Lessons Learnt

Lessons Learnt Report: Limitation of the Dopant Contrast Imaging Technique

Project Name: Local doping using Laser Chemical Processing technology for advanced silicon solar cells

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

Key learning

A (likely fundamental) limitation was identified to the Dopant Contrast Imaging technique that was developed as part of this project. It was found that quantitative imaging of n-doped samples – in other words, the determination of the actual concentration of n type dopant atoms from the microscope images – is not possible for any of the broad range of microscope settings investigated.

Implications for future projects

This particular lesson was an outcome of the research and research was required to come to this conclusion.

Knowledge gap

N/A

Background

Objectives or project requirements

The aim of this task of the project was to develop the Secondary Electron microscopy Dopant Contrast Imaging (SEMDCI) technique to the point where it can be reliably used for the production of quantitative dopant density maps from laser doped regions.

Process undertaken

To establish the relationship between dopant image contrast and dopant density, diffused samples were prepared. Since these samples display laterally uniform doping profiles over large areas, the doping profiles can be accurately determined using electrochemical capacitance-voltage (ECV) profiling. The same samples were then assessed under the SEM using various microscope parameters, and the contrast-dopant density relationship was determined. If the same relationship is determined for many different doping profiles, then the relationship can be considered robust and can be applied to the investigation of laser doped regions.

For p-doped region, it was possible to establish a consistent relationship between contrast and doping concentration, as shown in fig. 1 below.
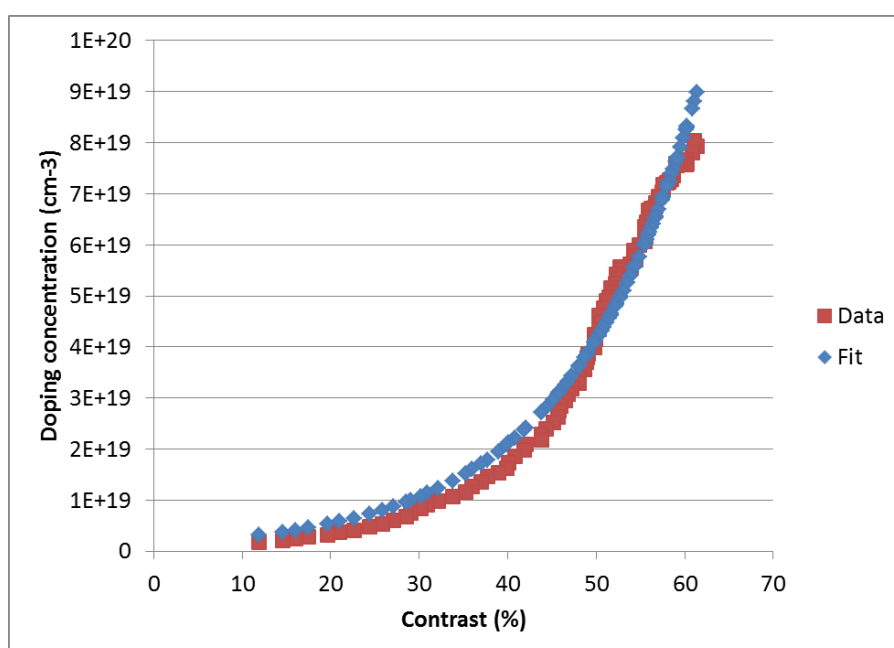

Fig. 1: Relationship between SEM contrast and doping concentration for p-type dopants.

For n type dopants, the same process was followed. However, in this case, such a relationship could not be established, as shown in fig. 2. A unique relationship between dopant concentration and image contrast can only be obtained if dopant concentration is the primary determinant of contrast. For n-type dopants, this is not the case, and so it is not possible to determine doping concentration maps from the microscope images. The evidence we have suggests that it is fundamentally not possible to arrive at a relationship between dopant contrast and concentration for n type dopants.
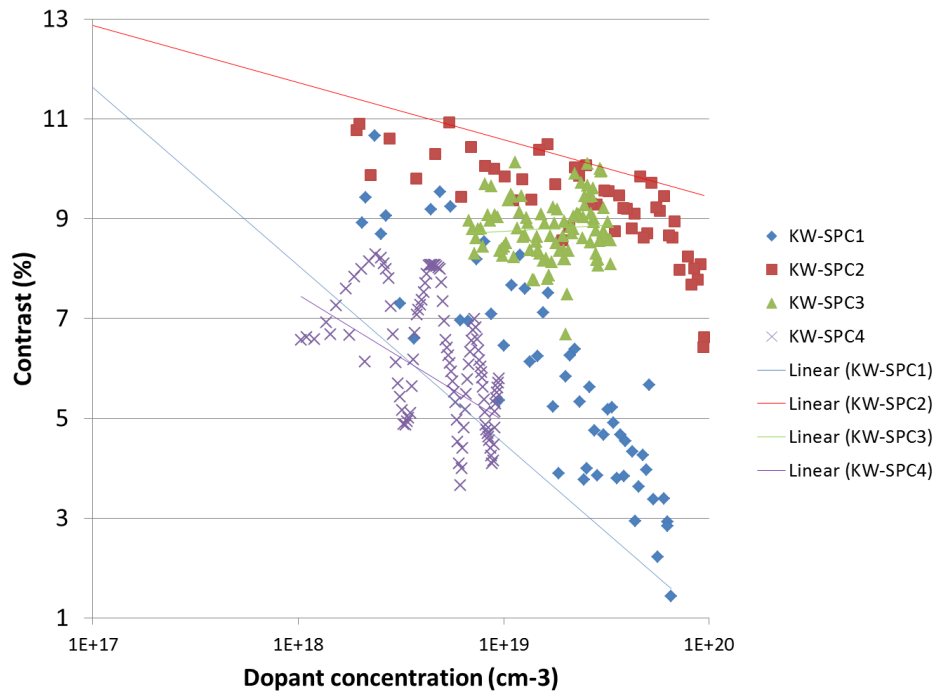
Fig. 2: Relationship between SEM contrast and doping concentration for n-type dopants, for various samples.