SCANNING SPREADING RESISTANCE MICROSCOPY
Overview

- Introduction
- How it works
- Scanning Spreading Resistance Microscopy vs Spreading Resistance Probe
  - Carrier spilling effects
- Sample preparation
- Resolution
- Quick summary
Introduction

- Necessary to understand how dopants are distributed after processing steps
- 1D doping profiling no longer accurate enough
- Non-classical device geometries require knowledge of how dopants are distributed in more than just one direction
SSRM is one such technique
It is based on Atomic Force Microscopy
Extension of the Spreading Resistance Probe (SRP) to micro and nano-scale
Used for cross-sectional measurements and 2D carrier profiling
Developed at IMEC in the beginning of the 1990s

- Measures cross-sections as opposed to SRP which measures bevelled surfaces
- An advantage with this is that carrier spilling effects are avoided
- This makes the interpretation of the results more straightforward
How it works

- A conductive AFM-probe is scanned across a sample surface at a high force.
- The high force is necessary to make the probe contact resistance and noise level as small as possible.
- This makes the spreading resistance the dominant contribution to the resistance.
- Spreading resistance definition: “[R]esistance of semiconductor defined by the distribution of dopant atoms in the direction normal to its surface.”
Sketch of SSRM setup

Conductive AFM probe

$10^{-12}$ to $10^{-4}$ A

to ADC

log(l)

bias voltage (50-500 mV)

Back contact
The local carrier concentration can be found by using the formula $R = \rho / 4a$

This equation is valid for a semi-infinite uniformly doped sample with an ohmic contact which does not penetrate into the sample.

It does not include probe shape, the force applied, the surface state concentration or the roughness of the sample surface.
To account for a non-linear relationship between the resistivity and the measured resistance, a term is added: \[ R = \rho/4a + R_{\text{barrier}}(\rho) \]

The total measured resistance also depends on the entire surrounding doping profile and a correction factor is added: \[ R = CF(a,\rho) \rho/4a + R_{\text{barrier}}(\rho) \]

With good measurement conditions SSRM has a low level noise and a wide dynamic range
- Due to the high forces applied during measurement the tip has to be very hard.
- For this reason the tip is often made of diamond, either by coating or a full diamond tip.
- Because diamond is normally a semiconductor it has to be doped to become conductive.
- Sample degradation is a problem. A proposed solution is to use pulsed rather than continuous force.
SSRM vs SRP
The difference between SSRM and SRP is shown in the figure

SRP is a dual probe technique

Whereas SSRM uses a conductive AFM tip to scan a device with a common electrode

Conductive-AFM and SSRM function identically, except that in SSRM a cross-sectioned surface is scanned, while in conductive-AFM a generalized surface is scanned
In SRP the spreading resistance is determined by measuring the voltage drop between the probes when a known current is applied between the electrodes.

By using Ohm’s law the spreading resistance can then be calculated.

The following expression gives the resistivity in the case of a two-probe system: \( \rho = 2R_{SR} \alpha \)
Carrier spilling effects

- Describes the diffusion of free carriers in a device
- Happens when two semiconductors are brought together to form a PN-junction
- Free carriers will diffuse over the junction until the electric field and the diffusion force balance each other out
- This effect will cause disturbances in SRP measurements
## Differences between SRP and SSRM

<table>
<thead>
<tr>
<th>SRP</th>
<th>SSRM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performed on bevelled surface</td>
<td>Performed on a cross-sectioned surface</td>
</tr>
<tr>
<td>Makes use of two probes</td>
<td>Makes use of one probe and a back-contact</td>
</tr>
<tr>
<td>Size of probe contact: 2 µm</td>
<td>Size of probe contact: 10 nm</td>
</tr>
<tr>
<td>Probes separation distance: 15 µm</td>
<td>Separation distance between probe and back-contact: 1mm</td>
</tr>
<tr>
<td>Symmetry allows the Laplace equation to be solved in 1D, cylindrical symmetry</td>
<td>No cylindrical symmetry</td>
</tr>
</tbody>
</table>
Sample preparation

- The sample has to be prepared before measurement
- Involves two basic steps: Cross-sectioning and making an electrical back contact
- It is also possible to use bevelled sections
- The drawback is, as mentioned, that carrier spilling effects come into play when bevelled surfaces are used
- This also makes PN-junction delineation non-trivial
Making a back contact ensures that every doping region is in contact.

It also makes sure that there is a path where the current can flow from the contact region between the tip and sample to the back side of the sample.

If doping regions are not in contact, too high resistances may be measured.
Illustration of the steps involved in sample preparation
Crystal cleaving

- The surface to be investigated should be as smooth as possible
- Cleaving is one way to achieve a smooth surface
- To do this, the sample is first scratched by a diamond pen and the resulting scratch is aligned one of the crystallographic directions of the semiconductor
After this, the crystal is split into two parts by bending the wafer and letting the scratch advance through the material.

Semiconductors like InP and GaAs are easily cleaved without getting a rough surface.

These are therefore cleaved in the way described above.

The crystalline structure of the wafer makes sure the cleaving gives a straight cut.
Figure 4: A SSRM image showing a cleaved III-V semiconductor substrate to be processed to a hetero-junction bipolar transistor. This sample consists of different layers of n- and p-type GaInAs and GaAs. The different colours are different resistivities in the substrate. As mentioned, the low roughness of these semiconductors gives a clean image without topographic disturbances.
Cleaving silicon is more difficult.
For locally flat regions it is suitable.
The problem is knowing which parts of the sample that will have low and high roughness.
The surface often has a lot of topographic variations.
Cleaving can be used if the sample is sufficiently large, but in general it is not good enough.
If the sample has been through a metallization process there is another problem. The cutting line will bypass the contact and leave a hole or bump in the cross-section. This could cause the AFM tip to break during measurement. It could also lead to artefacts in the measured signal.
A non-flat cross-section caused by the cutting line circumventing the contacts.
Polishing

- For Si polishing has been proven to be more effective than cleaving.
- The sample is then polished with sandpaper, diamond, and finally Al2O3.
- This method provides a better compromise between low material selectivity and low surface roughness.
Making a back contact is easily achieved with a large sample.

A direct deposition of a conductive material gives the electrical contact.

With a smaller doping region it is more challenging.

A localized contact has to be made with high positional accuracy.

This is achieved with the use of a focused ion beam (FIB).
Resolution

- Resolution is sometimes defined as the ability of a technique to resolve a certain feature.
- However, both a poor and a good resolution can resolve a feature if the signal to noise ratio is high enough.
- A better definition is how accurately it can be resolved or the deviation from the ideal case.
Schematic showing two tips with different radius measuring a change in resistance when scanning across an insulating layer.
In an experiment two samples were cross-sectioned and then characterized, the first by SCM, the second by SSRM.

For the analysis, an oxide layer was formed by exposing the sample to ozone.

Biasing parameters were chosen to give the highest possible output signal.
The SCM profile shows some contrast between the layers, but it does not resolve the finer features.

This can be observed by looking at the peak to valley variation.

In the SSRM measurement diamond coated Si tips were used.

The force and the voltage were chosen to give the highest contrast.
The figures show the carrier concentration in arbitrary units as a function of sample depth.
For the SSRM a much higher peak to valley variation can be observed.
This gives a better contrast between the layers.
In addition, a lower value for the carrier concentration at the last of the minima can be observed.
The finer details of the carrier distribution in general are clearly resolved.
The comparison demonstrates the superior resolution of the SSRM over the SCM.

The smallest interaction volume of the SSRM gives a better spatial resolution than the same volume of the SCM.
Another sample, with the depth dimension enlarged by a factor of 3, was also characterized by SCM.

In this measurement the peak to valley variation was much higher.

The finer details which the technique failed to resolve in the previous sample, were now clearly resolved.
The SSRM gives a more detailed view of the dopant distribution and has higher spatial resolution than the SCM. This is caused by the smaller interaction volume. When the dimensions were increased the SCM resolved features that it previously could not. This indicates that the probing is performed over a larger region than the feature that is to be resolved.
Quick summary

- Need for 2D doping profiling
- Applications are exact PN-junction delineation and determination of carrier distribution in semiconductor materials
- Setup and functionality of SSRM
- Comparison between SSRM and SRP with a look at carrier spilling effects
- How the sample is prepared before measurement
- Resolution with a comparison between SSRM and SCM
References

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