

## SURFACE (PHOTO)VOLTAGE MONITORING IN ROLL-TO-ROLL DEPOSITION OF THIN FILM SILICON SOLAR CELLS

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**ABSTRACT:** The Kelvin probe is a non-contact, non-destructive vibrating capacitor device that measures the work function difference between a conducting sample and a vibrating tip. This contribution focuses on inline monitoring of the surface (photo) voltage of deposited silicon layers. We apply a custom-built in-situ Kelvin probe, operated in a roll-to-roll PECVD system, located immediately after the plasma zones to enable direct feedback to the controlling system of the plasma deposition. The surface photovoltage of nip thin film Si solar cells increases with increasing Voc. The results imply that inline, contactless measurements of the open circuit voltage are possible and that thus monitoring the doped layer quality during roll-to-roll production is feasible.

**Keywords:** a-Si solar cells, in-situ monitoring and diagnostics, large area deposition

### 1 INTRODUCTION

Roll-to-roll production of thin film Si solar cells has advantages over batch-type reactor systems, since it allows high-throughput fabrication and application of cheap foil substrates. The flexible substrate also allows new applications of PV in products, such as building integrated PV, which is the most important market in densely populated, developed countries [1,2].

ECN is developing a process for roll-to-roll production of high efficiency solar cells based on amorphous (a-Si:H) and microcrystalline ( $\mu$ c-Si:H) silicon thin films on steel foil, coated with an insulating barrier layer and sputtered back contact and reflector. The main purpose of the barrier layer is to enable monolithic series interconnection of cells after deposition of all layers [3]. As part of the pilot line, we have developed, in collaboration with Roth&Rau AG, a roll to roll PECVD system for the Si layer deposition. The Flexicoat300 has three deposition chambers and can handle webs with a width up to 30 cm [4].

In roll-to-roll production, inline quality assessment and control are of utmost importance. Being able to continuously check the quality of the deposited silicon, and instantaneously adjust the process when necessary without the need to first deposit hundreds of meters before the material can be taken out of the vacuum, will greatly enhance the yield. Non-contact measurements, such as spectral ellipsometry [5,6] and UV-VIS reflectometry [7,8], are preferred in order not to damage the surface of the deposited layers. Kelvin probe measurements are a good addition to the standard toolkit of optical measurements as they supply information on electrical properties without contacting the deposited layers, needing only electrical contact to the back side of the substrate.

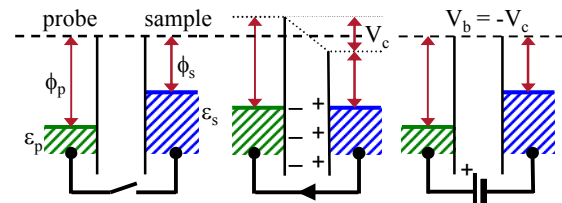
This contribution focuses on inline monitoring in the Flexicoat300 of the surface (photo)voltage of deposited silicon layers using an in-situ Kelvin probe developed in collaboration with KP Technology Ltd. in the so-called 'off-null' method [9]. We will present continuous measurements of roll-to-roll deposited Si layers with varying process parameters to evaluate the effective donor concentration of doped a-Si. Furthermore, using an in-situ illumination system with white light LEDs, we will also show the relation between the surface photovoltage and the open-circuit voltage of pin and nip thin film Si solar cells.

### 2 EXPERIMENTAL SETUP

#### 2.1 Kelvin probe principle

The Kelvin probe is a non-contact, non-destructive vibrating capacitor device to measure the work function difference between a conducting sample and a vibrating probe. Note that the work function is sensitive to the surface condition and also to external factors, such as illumination. The operating principle is sketched in Figure 1. Figure 1a shows the electron energy levels of tip and substrate in open circuit situation, where  $\phi_{p,s}$  are the work functions and  $\epsilon_{p,s}$  are the Fermi levels of probe and sample.

We can determine the work function difference  $\phi_s - \phi_p$  when the sample and the probe are short-circuited, (see Figure 1b) as electrons will flow from the higher work function material to the lower work function material, until the charge redistribution equalises the Fermi levels of both materials. The resulting contact potential  $V_c$  is equal to the work function difference  $\phi_s - \phi_p$ .



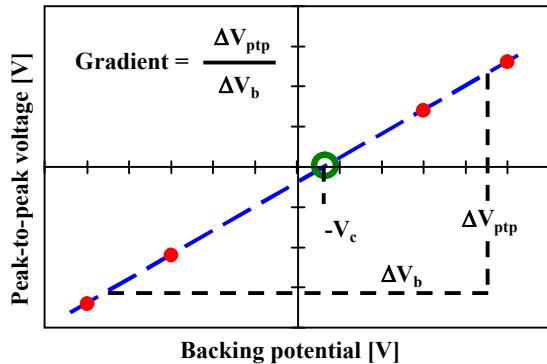
**Figure 1:** Electron energy level diagrams of sample and probe (a) without contact; (b) with external electrical contact and (c) after compensating the charge difference.

#### 2.2 Off-null method

The probe-sample configuration can be regarded as a flat-plate capacitor, which can be charged due to the work function difference. In order to determine the work function difference, i.e. the contact potential, one has to find the bias voltage (usually called a backing potential), at which the charge on the capacitor is null. This can be done, by vibrating the probe, i.e. varying the probe-sample distance, which changes the capacitance of the device. This cyclic change leads to an oscillating current that can be measured with a lock-in amplifier yielding a peak-to-peak voltage  $V_{ptp}$ . If the charge is zero, no current will be measured. Then  $V_{ptp} = 0$  and the backing potential equals minus the contact potential,  $V_b = -V_c$ .

However determining the exact voltage is difficult as  $V_{ptp}$  is very noise sensitive when this oscillating current approaches zero. An alternative method, that we applied

here, is to measure the Kelvin probe signal at positive and negative bias voltages far off-balance, the so-called ‘off-null’ method [9], as indicated in. Figure 2 By accurately determining  $V_{ptp}$  for four or more bias voltages, we can interpolate the data to  $V_{ptp} = 0$  to obtain the contact potential.

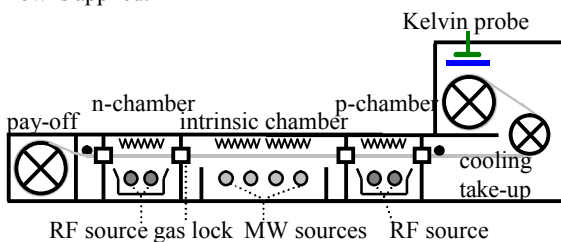


**Figure 2:** Sketch of the determination of  $V_c$ . The gradient is inversely proportional to the probe-sample distance.

### 2.3 In-situ installation

A vacuum compatible Kelvin probe, with an in-situ white light LED illumination unit, was custom built in collaboration with KP technology Ltd. The integrated white light LED illumination unit allows measuring the surface voltage under illumination. The Kelvin-probe-and-illumination unit fits on a regular DN40CF flange and thus is easily fitted to a vacuum system.

The Flexicoat300 is a joint development of Roth&Rau AG and ECN and contains 5 vacuum chambers: a pay-off chamber, 3 PECVD chambers for the deposition of intrinsic and n- and p-doped Si layers and a take-up chamber. The system is designed for continuous roll-to-roll deposition on moving foil substrates and can handle webs with a width of up to 30 cm. Figure 3 shows a schematic view of the Flexicoat300, highlighting the location of the in-situ Kelvin probe. We have been able to measure the Kelvin probe signal both in high-vacuum ( $10^{-4} - 10^{-6}$  mbar) and also during processing, when at  $\sim 0.1$  mbar a steady gas flow is applied.



**Figure 3:** Cross-section through the Flexicoat300 roll-to-roll coater.

## 3 RESULTS AND DISCUSSION

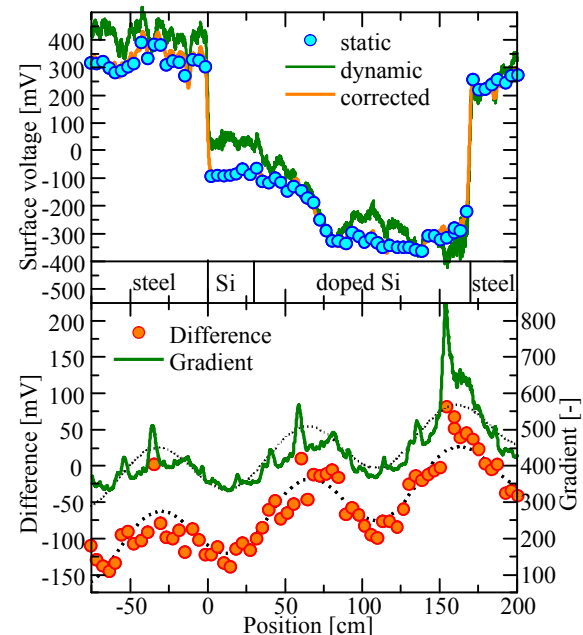
### 3.1 Roll-to-roll surface voltage measurements

We apply the Kelvin probe to in-situ roll-to-roll measurements of doped Si layers. The Si layers are deposited directly on the steel carrier foil. First, intrinsic Si was deposited on 50 cm of the foil. Then the  $\text{PH}_3$ -flow was increased stepwise during roll-to-roll deposition such that the effective donor concentration of the n-type a-Si layer should increase. The Si coverage ends at 170 cm.

To get an accurate picture of the changes of work

function over the foil, the work function was determined at 5-cm intervals. In this run, the gradient was adjusted to 500 a.u. for each measurement, whilst the foil was not moving. This assures us that the sample-probe distance remains constant. Figure 4 shows the scan of the surface voltage as a function of the position along the foil direction (blue circles).

Then, the work function was also measured in roll-to-roll mode with a web speed of 5 cm/min. Data points were taken every 0.88 sec, that is every 0.73 mm (green line in Figure 4). The work function was measured without adjusting the gradient. This causes a certain amount of deviation of the signal over time when the gradient (or probe-surface distance) varies. The gradient was also recorded and plotted in the bottom half of Figure 4.



**Figure 4:** Work function and gradient as a function of position on the foil. The dopant concentration increases from left to right in the ‘doped Si’ part of the scan. Static (roll-to-roll) measurements are shown as filled circles (solid lines). The corrected dynamic data (orange line) are adjusted to a gradient of 500 (see text).

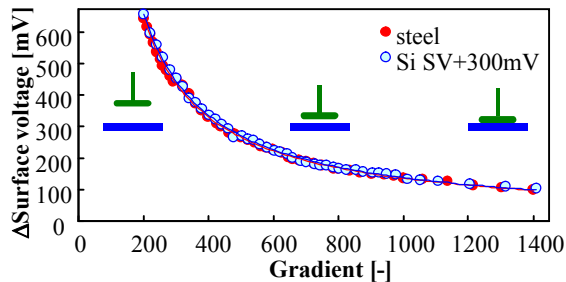
We see that the work function transient clearly shows the transition at 0 and 170 cm between steel and (doped) Si. Between 0 and 50 cm the work function is rather constant, corresponding to the intrinsic layer. Starting at 50 cm, the work function starts to decrease with increasing n-type doping concentration during deposition, as the work function is proportional to the natural logarithm of the donor density. For higher n-type doping concentration the work function stabilises, suggesting that the effective donor concentration in the n-type layer no longer increases.

We conclude that although the uncorrected dynamic measurements (green line) and the static measurements show the same qualitative behaviour in these preliminary scans, quantitatively there are some deviations.

### 3.2 Correction for sample-probe distance

Besides the work function difference, also the gradient  $\Delta V_{ptp}/\Delta V_b$  (see Figure 2) is recorded. It is well known that this gradient is inversely proportional with the distance between the sample and the probe tip. For an ideal Kelvin probe (infinitely large), this has no influence on the contact

potential. However, for finite probes and samples, the surface voltage depends on the gradient (and thus on the sample-probe distance too), as can be seen in Figure 5. The Figure also confirms that the curvature of the SV-Gradient relation is determined only by the set-up and local environment. Different sample material or surface conditions only affect the ‘height’ of the curve. This means that, for each measured pair of surface voltage and gradient, we can retrospectively calculate the surface voltage at any gradient *as if* it was measured at that gradient.



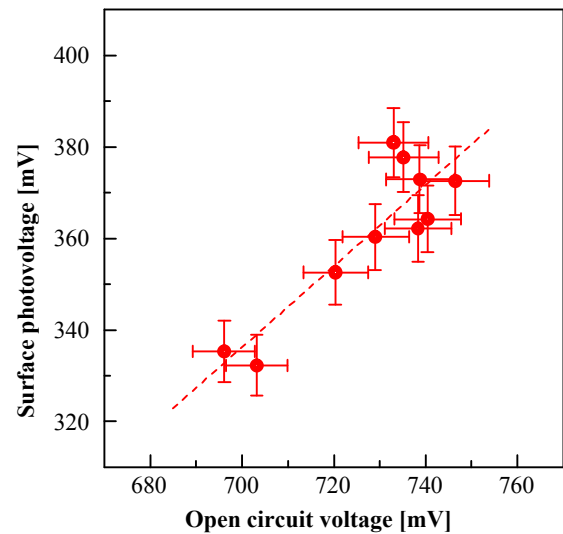
**Figure 5:** Surface voltage as a function of gradient measured on steel foil and silicon. The gradient is varied by changing the sample-probe spacing as indicated by the cartoons. The solid line is a fit, assuming that the surface voltage is inversely proportional to the gradient. Measurements on different materials show the same curvature, differing by a vertical shift only.

Now let’s return to the scan over the deposited layers on the foil. We have plotted the gradient, as recorded during the roll-to-roll measurement, as a function of the location in the bottom half of Figure 4. We see the same transient as for the calculated difference between the static and roll-to-roll scans. The gradient and difference data show a linear trend convoluted with a sinusoidal contribution, whose period is identical to the circumference of the pick-up roll. This strongly suggests that the variation in gradient (and the difference between static and roll-to-roll measurements) is due to the apparent non-roundness of the pick-up roll. It also means that we can and should correct the roll-to-roll data, using the recorded gradient and the known relation between gradient and surface voltage.

For the roll-to-roll measurements, we know the gradient at each data point. Applying the ‘master’ curve shown in Figure 5, we have corrected the measured surface voltage values to the corresponding values *as if* the roll-to-roll data were taken at a gradient of 500, because the static data points were measured at a gradient of 500 too. The corrected data is plotted in Figure 4 as the solid orange line. Clearly, the quantitative agreement with the static data points is excellent.

### 3.3 Surface photovoltage of a-Si pin cells

Finally, we look whether the Kelvin probe can be used to measure the open-circuit voltage directly, without the need of contacts. The surface photovoltage (SPV) is determined ex-situ for a range of pin a-Si solar cells on FTO-coated glass. The SPV is plotted against the open-circuit voltage in Figure 6. The samples were deposited with a variety of layer thicknesses and plasma conditions to create a range of open-circuit voltages. Despite relatively large error bars, we discern a more or less linear relation between the SPV and the  $V_{oc}$ .



**Figure 6:** The surface photovoltage as a function of the open-circuit voltage for a-Si pin cells on Asahi glass. The dashed line is a linear fit.

In the ideal case, the change in surface voltage upon illumination with the solar spectrum should be the open-circuit voltage. In Figure 6, we observe a large difference in the absolute value. This difference is related to two main differences in the measurement set-up. i) Whereas the  $V_{oc}$  is measured with light on the p-side, the SPV is illuminated from the n-side. ii) The  $V_{oc}$  is determined with the AM1.5 spectrum; however the intensity of the LED illumination in the SPV is only about a third of that. Furthermore, the spectral distribution of the LED light is quite different from the solar spectrum. This confirms that the KP measurement is very sensitive, both to sample (surface) properties and to environmental variables. Nonetheless, when everything else is constant, we observe a linear relation between the SPV and the  $V_{oc}$ . At the current state of knowledge, we can estimate the  $V_{oc}$  for an independent substrate with an accuracy of  $\pm 25$  mV. We are positive that for measurements along a roll-to-roll deposited solar cell stack, this accuracy will be much better.

## 4 CONCLUSIONS

We have shown inline, contactless measurements under deposition conditions using an in-situ Kelvin probe equipped with a LED illumination unit. The surface photovoltages of pin a-Si solar cells are linearly related to their open-circuit voltages, when the Kelvin probe samples are prepared in the same way. Furthermore, the Kelvin probe can be operated in-situ during roll-roll Si deposition, recording the donor density variation along the foil by way of the work function. The roll-to-roll measurements, when adjusted for variations in measured gradient, show an excellent agreement with static data.

To conclude, we have shown that the inline Kelvin probe can be used to continuously monitor the doped layer quality and the open circuit voltage during roll-to-roll fabrication.

## ACKNOWLEDGEMENTS

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