ACCURATE MEASUREMENT OF EXTREMELY LOW SURFACE RECOMBINATION VELOCITIES

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We report a simple technique to determine the surface recombination velocity of silicon and other semiconductor surfaces which have been passivated with a dielectric layer, as a function of charge density. A double sided metal-oxide-semiconductor structure, employing large area, partially transparent metal contacts, is used to enable charging of the surfaces. Simultaneous measurement of the emitter saturation current density J_{oe} and the effective instantaneous lifetime τ_{inst} allows accurate extraction of the effective surface recombination velocity S_{eff} at any given injection level. Extremely low J_{oe} values down to 0.7 $fAcm^{-2}$ per side are measured on the Si-SiO_2 interface of a thermally oxidised, charged wafer.
Keywords: silicon, SiO_2, charge, inversion-layer

1 INTRODUCTION

It is well known that presence of electrical surface charge can have a dramatic effect on the recombination rates of excess carriers at the surfaces of Si solar cells and other devices, as a result of band bending induced at the Si surface. On lightly to moderately doped silicon, the presence of a large amount of either positive or negative charge leads to low surface recombination rates corresponding to accumulation or strong inversion conditions at the surface, while the recombination rate reaches a maximum when the surface is in depletion, with approximately equal concentrations of electrons and holes. Even on diffused surfaces, the presence of charge can have a dramatic effect on the electrical interface properties. While measurements carried out to date have clearly shown the qualitative variation of the surface recombination rate with charge density, accurate determination of surface recombination becomes difficult as the surface recombination rate approaches very low values.

The application of surface charge to silicon has been used before as a tool for characterization, most commonly with the use of corona discharge, which ionizes air particles with a strong electric field so that they are deposited onto the surface of an insulated semiconductor such as silicon with a silicon dioxide layer (Si-SiO_2) [1][2]. A drawback of this method is that a kelvin probe must be used to quantify the charge applied. In addition, the use of a corona discharge has been observed to be able to result in a modification of the interface defect properties [3][4][5]. We have therefore developed a method whereby a known quantity of charge can be applied while simultaneously measuring τ_{eff} and J_{oe}. This allows S_{eff} to be determined, giving valuable information about the Si-SiO_2 interface. In addition, the method allows accurate determination of the bulk lifetime. Measuring samples under strong accumulation allows direct comparison between the surface recombination of different surface orientations, or of surfaces with different diffusion profiles[6][7].

2 EXPERIMENTAL

2.1 Sample Preparation

Samples used for lifetime-voltage measurements were p type, float-zoned, (100), >100Ω/cm, 500µm thick Si wafers. After etching in acid solution and a standard RCA cleaning, samples received a passivating oxide of around 90 nm that was thermally grown at 1000°C in dry oxygen with an in-situ anneal in nitrogen, followed by annealing in forming gas (FGA, 5% H_2 in 95% Ar) at 400°C for 30 min. A thin layer of aluminium (approx 5 nm thick) was evaporated onto both surfaces of the sample, so that there was at least 5 mm overhang over the photo-conducting coil of the lifetime tester during measurement. This thickness was carefully chosen to ensure minimal interference with the lifetime measurement, and the transmission of sufficient light for the lifetime measurements. Contact to Al layers was made using conductive silver paste, while contact to the silicon bulk was made by removing a small amount of oxide in one of the corners of the sample and applying silver paste. Fig 1. gives an indication of the final set up of the experiment.

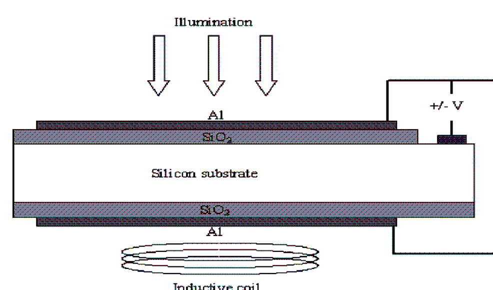

Fig 1: Sample ready for lifetime measurement with known voltage applied.

2.2 Measurements

Measurements were carried out using the inductively coupled photoconductivity decay technique [8][9]. The effective lifetime is determined from the rate of decay of

the wafer photoconductivity following the application of a light pulse. In high-level injection, the instantaneous decay time τ_{inst} is

$$1/\tau_{inst} = 1/\tau_{bulk,hli} + (2J_{oe}n)/(qWn_i^2) \quad (1)$$

Where $\tau_{bulk,hli}$ is the high level injection lifetime of the wafer bulk, n is the photo-generated excess carrier density in the wafer bulk, W is the wafer thickness, n_i is the intrinsic carrier concentration, J_{oe} is the emitter dark saturation current density and q the electronic charge.

2.3 Effect of the presence of metal layer on lifetime measurements

To ensure that the metal did not interfere significantly with the lifetime tester coil during lifetime measurements, a test was carried out using lightly phosphorus diffused wafers with sheet resistance 200 Ω/square cm, with a thermally grown, 50 nm thick oxide and a 50 nm thick layer of silicon nitride deposited by low pressure chemical vapor deposition (LPCVD). Thin layers of Al were progressively evaporated on both sides of the samples and J_{oe} and τ_{eff} were monitored. The use of an LPCVD nitride layer in addition to the oxide has been found to minimize the risk of sample contamination during metal evaporation. J_{oe} can be observed in Fig 2. It can be seen that the evaporation of metal results in a slight change in J_{oe} of up to 6%. This difference has been deemed within the acceptable range of error for the measurements.

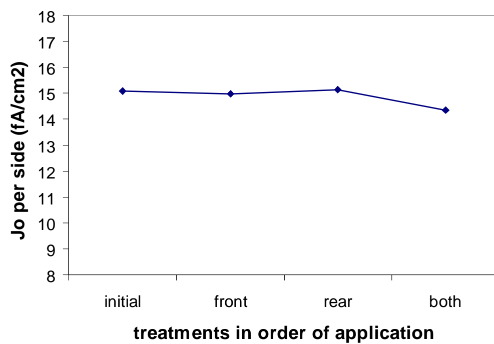

Fig 2: Joe per side with addition of metal.

2.4 Leakage current

Leakage current was found to be in the order of <100 μA at an applied voltage bias of ±32 V. A leakage current of this magnitude is sufficiently small not to result in a significant potential drop over the sample area. However, higher leakage currents up to 100 mA were observed with approximately half of undiffused samples with a thinner oxide (50 nm). Leakage currents of this magnitude make interpretation of the results very difficult, and these samples were not evaluated.

3 RESULTS AND DISCUSSION

τ_{inst} was recorded as a function of voltage bias in the range -32 V to +32 V (see Fig 3.). The corresponding applied charge density varies from -7.6×10^{12} cm^{-3} to $+7.6\times10^{12}$ cm^{-3}. The curve displays the characteristic 'U' shape seen in studies with corona discharge and kelvin probe measurements, with a minimum in the effective lifetime around -1.2V. The work function difference of the Al-SiO_2-Si system for the sample used is ~-0.8V. If we assume that the minimum in the effective lifetime curve corresponds to a depleted Si-SiO_2 interface, we can estimate the effective charge density due to fixed oxide charges to be 1×10^{11}cm^{-3}.

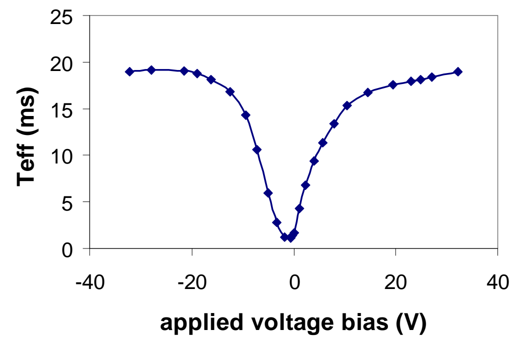

Fig3: Effective lifetime measured at an injection level of 4×10^{15} cm^{-3} as a function of applied voltage. Undiffused high resisitivity p-type silicon with oxide.

Fig. 4 shows the measured values for the emitter saturation current density J_{oe} on the same sample. Values as low as 0.7fAcm^{-2} are obtained in accumulation. At such low values of Joe, Auger recombination is likely to introduce significant error to the measured values, due to uncertainties in the Auger recombination parameters and possible error in the measured value of the excess carrier density, used to determine the Auger recombination contribution.

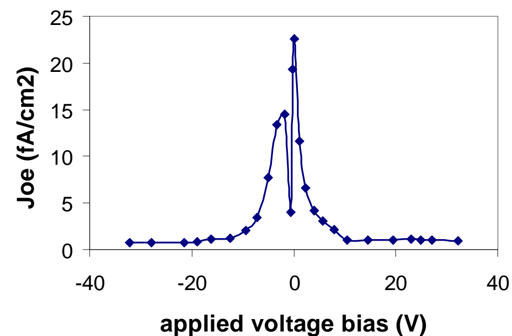

Fig4: J_{oe} per side as a function of applied voltage.

A valid measurement of J_{oe} can only be made under the conditions that i) the surface of the sample is in low level injection and ii) the bulk of the sample is in high level injection (as a general rule, n should be at least equal to $10n_o$). Both conditions must be met over the entire injection level range used to extract the value of J_{oe}. Condition ii) is met over the entire range of V_{app}, but condition i) clearly is not met for low values of V_{app}. Calculation of the surface doping concentration as a function of applied charge density shows that the electron or hole concentration exceeds 10^{18} cm^{-3} for applied voltages of greater than 1.5 V or less than –3.9V, respectively. Note that while J_{oe} usually includes contributions from both the bulk and the surface regions, due to the extremely sharp carrier profile in the silicon

surface region resulting from the applied charge, the contribution from the silicon bulk is negligible in this case.

For the range of applied voltages where a measurement of J_{oe} is valid, the corresponding value of S_{eff} can be determined from:

$$S_{eff} = J_o(p_o+n)/(q.n_i^2) \quad (2)$$

We used the lowest value of S_{eff} (and the corresponding highest value of τ_{inst}) determined in this way (at V_{app}= -32V) to determine the bulk lifetime from

$$1/\tau_{eff} = 1/\tau_{bulk} + 2S_{eff}/W \quad (3)$$

S_{eff} can then be determined over the entire voltage range from eq. 3, and over the restricted range of voltages from eq. 2. S_{eff} was determined to be as low as 0.3 cm/s at the injection level of $4x10^{+15}$ used for measurements. Values determined by both τ_{eff} and J_{oe} are in good agreement as can be observed in Fig5.

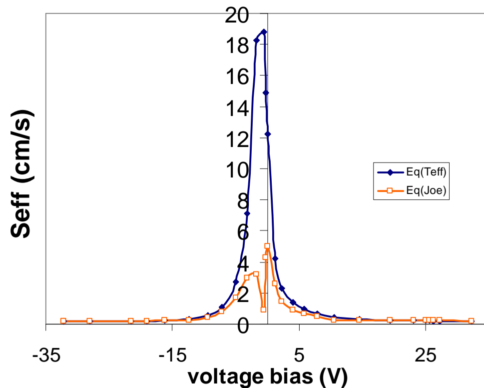

Fig5: Seff values as determined from both Teff and Joe

The lowest measured Joe value from Fig. 3 is ~0.7fA/cm^2 per surface for V_{app}= −32 V. Such a value of J_{oe} on both surfaces would impose a limit on the open circuit voltage of a solar cell of 817mV, assuming a short circuit current of 40 mA/cm^2.

3 CONCLUSION

Although a small loss in sensitivity of the lifetime tester coil is observed, this method is a valuable tool for observing the effect of surface charge on the properties of
a semicondtuctor sample, and can also provide field effect passivation in order to allow an opportunity for comparing different surfaces. The method shows the huge effect surface charge can have on surface behaviour and quality of a solar cell, and indicates that future awareness of these properties within operating modules may be nessesary for further solar cell improvement.

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