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Effect of non-Ohmic back contacts in capacitance transient measurements on hydrogenated amorphous silicon

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A comparison of capacitance transient measurements on Schottky diodes with identically doped n-type a-Si:H but different backside electrical contacts demonstrates a pronounced distortion of the capacitance transient when the back contact is the p^+-type crystalline Si (c-Si) substrate. In particular, the capacitance transients for diodes on p^+-type c-Si display a pronounced dependence on the width of the trap-filling voltage pulse, and the charge flowing into the device does not saturate as in a near-ideal capacitor but rather continues to increase with a $\log_{10}(t)$ dependence even for times $t \geq 100$ msec (at 300 K). The results for the p^+ contact are identical to previously published results but are not observed on Ohmic n^+-type a-Si:H/Cr contacts. The results demonstrate the critical importance of utilizing Ohmic backside contacts for interpreting capacitance transients in terms of bulk defects in a-Si:H.

Capacitance transient spectroscopy has often been used on hydrogenated amorphous silicon (a-Si:H) to characterize deep-level defects in the bulk of the material.[1–4] It was recently reported that such capacitance transient measurements exhibit an anomalous dependence on the duration of the trap-filling pulse: longer trap-filling times result in longer capacitance relaxation times.[5,6] This effect was attributed to a process occurring within the bulk of a-Si:H whereby the depth of a deep level depends on the time of occupancy; that is, the longer the trap is occupied, the deeper the state and hence the longer the emission time.[5,7] The time scale for this process is unusual in that it is on the order of 1–100 msec, a time much too long to be accounted for by the usual lattice relaxation times. This effect, if confirmed, could provide information about metastability and defect formation processes in a-Si:H.

To characterize deep levels in a-Si:H (or in a crystalline semiconductor) by capacitance transient spectroscopy, defects in the depletion region of a reverse-biased Schottky diode are first filled with majority carriers (e.g., electrons) by momentarily decreasing the magnitude of the reverse bias, which collapses the width of the depletion layer and thereby provides free electrons for capture. The additional charge is supplied through the backside contact.[1] After removal of this "trap-filling pulse," the device capacitance is monitored as the charge density in the depletion layer increases due to thermal emission of electrons from the newly filled deep levels. The temperature dependence of the capacitance relaxation time(s) relates to the activation energy(ies) for thermal emission from deep levels, and the magnitude of the capacitance change depends on the density of deep-gap states.

Unlike other defect spectroscopies, the capacitance transient measurement is performed on an electronic device such as a Schottky-barrier diode in which one contact is rectifying and the other is Ohmic. While the need for a low-leakage rectifying contact is widely recognized, the requirement for a low-resistance, nonrectifying back contact is less well appreciated. The measurements exhibiting the anomalous dependence on filling time were performed on devices in which the n-type a-Si:H layer was deposited directly onto a p^+-type crystalline silicon (c-Si) substrate.[5,6] One stated rationale for employing such a back contact is the ability to also utilize it as a blocking (front) contact by reversing the polarity of the bias.[8] Unfortunately, filling-pulse-width measurements place stringent demands on the electrical characteristics of the backside contact. Not only must the contact deliver current under dc conditions, it cannot impede charge flow into or out of the device on time scales comparable to the emission and filling-pulse times.

Because the results demonstrating the bulk relaxation process were performed on devices with non-Ohmic, nonstandard back contacts, we attempted to confirm the anomalous filling-time results using the recognized standard Ohmic back contact consisting of n^+-type a-Si:H on a metal film. A straightforward approach was adopted to investigate the effects of the backside contact on the filling-pulse-width dependence of the capacitance relaxation process: the capacitance transients were recorded on a set of devices fabricated with the same bulk layer of a-Si:H and the same Schottky contact but with different backside contacts. If the anomalous filling-pulse effect were characteristic of bulk material, then the results should not be affected by the use of an Ohmic back contact. The results presented here demonstrate that the *non-Ohmic contact*, rather than a bulk relaxation process, can fully account for the anomalous diode response in the capacitance transient measurement.

Two sets of devices were fabricated, including the same semiconducting a-Si:H layer and rectifying contact but different back contacts. The common semiconducting layer (2.3 μm thick) was deposited by conventional glow discharge deposition from silane at a substrate temperature of 250 °C, with the inclusion of 20 ppm PH_3 in the gas phase to produce doped n-type conductivity. The first set of diodes utilized the standard Ohmic back contact: the substrate consisted of a Cr film (100 nm thick) vacuum deposited onto a degenerately doped single-crystal Si wafer, with an Al film deposited onto the back surface of the wafer. Directly onto the Cr film was first deposited a heavily phosphorous-doped layer of a-Si:H (100 nm thick) to provide an Ohmic n^+-type conducting layer/Cr contact. Over this layer the semiconducting a-Si:H layer was deposited. This will be designated as the "Cr/n^+" back contact. The second set of devices utilized the back contact described in Refs. 5 and 6, that is, the semiconducting layer was deposited directly onto a polished, freshly wet-chemically-cleaned wafer of single-crystal silicon that was heavily boron-doped for p^+-type conductivity; an Al film was deposited onto the back surface of the wafer. This will be referred to as the "p^+-type *c*-Si" back contact. A portion of each of the above as-deposited specimens was illuminated with IR-filtered white light ($\sim$500 mW cm^{-2}) for three days to increase the density of deep-gap states and form the "light-soaked" samples. On all four of the above combinations of specimens, diode fabrication was completed with the formation of a Schottky-barrier contact on the semiconducting *a*-Si:H layer by vacuum evaporation of Pd through a shadow mask ($\sim$1-mm-diameter dots).

The activation energy for the electrical conductivity was determined, in the usual way, for each device, under reverse bias, from the temperature dependence of the capacitance as a function of frequency.[8] This energy relates to either the barrier at the contact or the activation energy of the bulk conductivity, whichever is the largest. For the as-deposited devices, the Cr/n^+ contact yielded an activation energy of only 0.23 eV as compared to 0.55 eV for the p^+-type *c*-Si contact; the difference suggests that the Cr/n^+ contact is indeed more Ohmic. Light soaking increased the activation energy to 0.53 eV for diodes with the Cr/n^+ contact and to 0.63 eV for the devices with the p^+-type *c*-Si contact, reflecting a substantial shift of the Fermi level to greater depths in the mobility gap due to light-induced defects.

The capacitance transient measurement conditions were chosen to allow direct (qualitative) comparison with the results of Refs. 5, 6, and 8. The small-signal differential capacitance was monitored at a frequency of 10 kHz, and the device temperature was 330 K. The filling pulse widths varied from 100 μsec to 1 sec, and the time-resolved capacitance transients were digitized at a 20-msec sampling rate. The diodes were reverse biased at 3 V, and the deep-gap states were filled by pulsing to zero bias. Since the effective donor concentration monotonically increases with time in the depletion layer[9] at a rate detectable even at 300 K, the depletion capacitance slowly increases with time under reverse bias. This phenomenon is apparently due to thermal dissociation of PH complexes and possibly a net transport of unbonded hydrogen out of the depletion layer.[10] Because of this effect, a systematic measurement cycle was implemented as follows: the device was allowed to relax under zero bias for about 30 min after the previous measurement. The 3-V reverse bias was then applied (for $\sim$10 min) until a preselected reference capacitance was obtained. Then the device was pulsed to zero bias for a specified pulse duration, and the capacitance transient was recorded under the 3-V reverse bias. The cycle was repeated for each pulse width. Although the results were not dependent on the pulse/bias procedure, the above protocol gave highly reproducible transients with nearly identical asymptotic values, which facilitated direct comparison of the transients and data analysis.

Capacitance transients are shown in Fig. 1 for three of the four types of devices and for a range of filling pulse widths for each device. The transients for the diodes with the Cr/n^+ contacts, both light-soaked and as-deposited, exhibited very little variation with pulse width; that is, the transients are essentially saturated even for the shortest pulse width of 100 μsec. The small dependence on pulse width is expected from conventional trap-filling kinetics due to the variation of the band potential (which determines the local free-electron density) with depth in a zero-bias depletion layer.[11] The lack of an anomalous filling-pulse-width dependence in both the as-deposited and light-soaked Cr/n^+ contacted diodes establishes that the filling-pulse anomaly is not due to bulk properties of *a*-Si:H. In other words, the anomalous pulse-width dependence reported in Refs. 5, 6, and 8 depends neither on the position of the bulk Fermi level nor on the density of electrons in the conduction-band tail states. The activation energies of our two diodes differ by 0.4 eV, yet both exhibit emission transients that are virtually independent of filling pulse width.

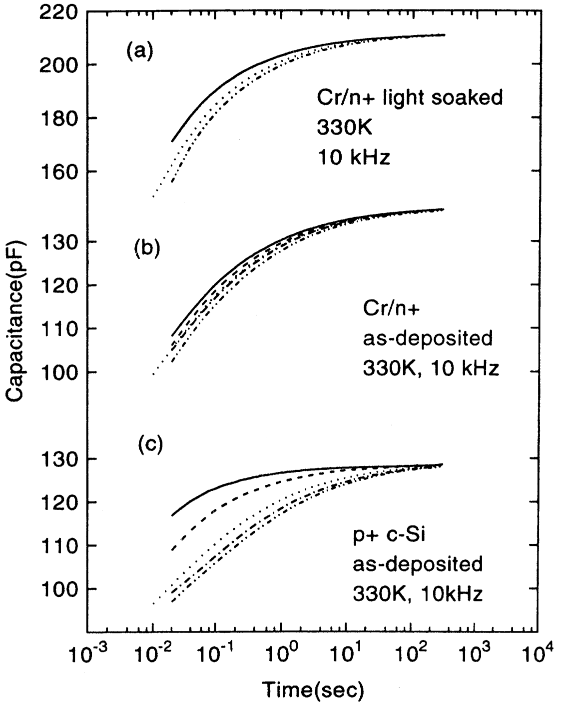

FIG. 1. The 10-kHz capacitance transient is plotted as a function of time at -3 V following a filling pulse to 0-V bias. The duration of the filling pulses are 0.1 msec (solid), 1.0 msec (dashed), 10.0 msec (dotted), 100 msec (dot-dashed), and 1 sec (double dot-dashed). The curves are presented for (a) a light-soaked diode with a Cr/n^+ backside contact, (b) an as-deposited diode with a Cr/n^+ contact, and (c) an as-deposited device with p^+-type *c*-Si for a backside contact. The semiconducting *n*-type *a*-Si:H layer (P-doped at 20 ppm) is the same in all devices.

The transients for the p^+-type *c*-Si contacted devices, on the other hand, exhibited a pronounced variation of relaxation time with filling pulse width for both as-deposited and light-soaked samples. Because the transients for the p^+-type *c*-Si contacts for as-deposited and light-soaked samples are similar, only results for the as-deposited cases are displayed in Fig. 1. The time interval over which significant capacitance relaxation occurs increases by almost two orders of magnitude as the filling pulse width is increased from 100 μsec to 1 sec. The results agree in detail with those

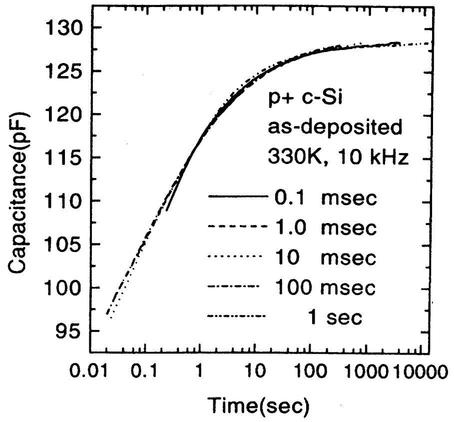

FIG. 2. The capacitance transient curves of Fig. 1(c) replotted by shifting the time axis to achieve overlap.

of Ref. 5. Furthermore, the shape of the transients for the p^+-type *c*-Si contacts are different from those for Cr/n^+ contacts. The transients from devices from the Cr/n^+ contacts continue to increase in slope at shorter times, while the slopes of the transients on diodes with the p^+-type *c*-Si contacts appear to decrease proceeding to shorter times.

In order to further illustrate the effects of a non-Ohmic back contact on the capacitance transients, we demonstrate that the set of transients for the as-deposited p^+-type *c*-Si contacted device can be superimposed by a simple parallel shift in $\log_{10}(t)$. Figure 2 shows the transients of Fig. 1(c) translated horizontally along the log-time axis for maximum overlap. The capacitance transients for various filling pulse widths appear to be nearly the same shape consistent with previous anomalous filling time measurements in Ref. 5. The emission time is approximately proportional to the square root of the filling time.[5,6]

Another approach that has been proposed to qualify back contacts utilizes the current transient that is induced upon application of the trap-filling voltage.[8] This method was evaluated in the present study by monitoring the induced current as a function of time after the applied voltage was changed from a reverse bias of 3 V to 0. The integral of this current yields the charge flowing into the device as a function of time, as shown in Fig. 3 on a log-time axis. One curve depicts charge flowing onto a 100-pF reference capacitor. The charge increases until it reaches $\Delta Q = 0.3$ nC, consistent with the 3-V step. The transition time for ΔQ is determined by the shape and rise time of the leading edge of the voltage pulse from the pulse generator, which were selected to be Gaussian and 80 μsec, respectively. After the requisite charge flows onto the capacitor, there is no further change for three decades of time. The change in ΔQ at yet longer times is due to time integration of small offsets (i.e., baseline errors) in the current and voltage amplifiers. A device suitable for transient measurements should exhibit characteristics similar to those for the 100-pF reference capacitor.

For the Cr/n^+ contacted diodes, charge flows into the device within 100 μsec of the application of the pulse. As in the 100-pF capacitor, diode charging is complete by about 1 msec. The saturation of the injected charge demonstrates that the charge is rapidly injected through the backside contact into the bulk where charge capture takes place. Saturation of the injected charge also occurs for the light-soaked Cr/n^+ contacted diode despite its larger activation energy.

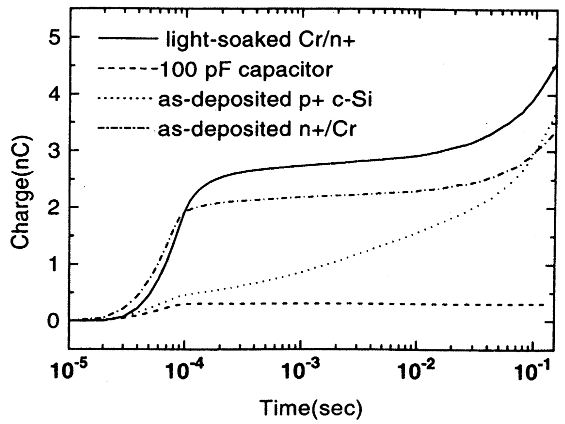

FIG. 3. The integrated charge flowing to devices during a filling pulse (a -3- to 0-V step) as a function of time for a light-soaked diode with a Cr/n^+ contact, a 100-pF reference capacitor, an as-deposited device with p^+-type *c*-Si contact, and an as-deposited diode with a Cr/n^+ contact. The charge necessary to charge the geometrical capacitance is about 0.15 nC. The p^+-type *c*-Si contact clearly exhibits delayed charge flow into the depletion region of the device.

In contrast to the above, the p^+-type *c*-Si contact impedes charge flow: charge continues to flow into the device even for times greater than 100 msec after the bias change. Our results are similar to those found in Ref. 5. Thus, the density of conduction electrons, required to fill bulk traps, continues to increase during the filling pulse. This contact-related charging characteristic accounts for the anomalous dependence of the capacitance transient on filling-pulse duration reported in Ref. 5. At long times, the bias history of the device can be important. Since a reverse bias creates donors and defects which affect the leakage current, and, therefore, the baseline current at long times, the charging curves at times longer than about 100 msec display large variations from run to run, and can either increase further or decrease toward zero. The shape of the charging curve for the device with the p^+-type *c*-Si contact is essentially identical to that reported in Ref. 8 for p^+-type *c*-Si contacts with a faster pulse rise time than used here.

The results in Fig. 3 suggest that the p^+-type *c*-Si contact impedes charge flow at short times, while at long times (>100 msec) the contact appears to deliver sufficient charge. Thus, the anomalous filling time results in Ref. 5 appear to reveal a time-dependent charge injection phenomenon at the back contact. Due to the complexity of the device structure and the field distributions through the device, one can only speculate that the effect may be due to changes in tunneling through barriers, the redistribution of charge, or other processes. Such effects may be important for understanding the transient behavior of electronic devices that incorporate such p^+-type *c*-Si contacts.

In summary, the comparison of devices with the same bulk *n*-type amorphous silicon and rectifying contact but different back contacts shows that the back contact can significantly distort capacitance transient measurements. The anomalous filling results are observed for p^+-type c-Si contacts but not for Ohmic Cr/n^+ contacts for the same bulk material. Effects associated with novel contact properties include an anomalous dependence of the capacitance transients on filling pulse width, $\log_{10}(t)$ charging curves, and anomalous flattening of the capacitance transients at short times that are not due to a dominance of charge emission in the relaxation process. Thus, the previously reported anomalous dependence of capacitance transients on pulse width is likely due to transient characteristics of the backside contact. This work suggests that a Cr/n^+ contact is significantly more suitable than a p^+-type c-Si contact for capacitance transient measurements of bulk material. The results also suggest that backside contact injection could also be a problem for filling-pulse measurements on p-type a-Si:H. Because of the difficulty of forming a contact to p-type a-Si:H with electrical properties equivalent to the Cr/n^+ contact for n-type a-Si:H, a systematic investigation of contact properties must be undertaken before meaningful capacitance transient data can be obtained on p-type a-Si:H.

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