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Measurement of Electron Density and Mobility in P-doped a-Si:H and mc-Si:H Films

By

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The electron density and mobility in P-doped a-Si:H and mc-Si:H films are measured by conductivity and sweep-out experiments as a function of measurement temperature and annealing temperature. The conductivity activation energy is found to be 0.30 eV for a-Si:H and 0.035 eV for mc-Si:H with doping levels of $PH_3/SiH_4 = 2\%$ and 0.16%, respectively. The electron density is about $2.0 \times 10^{17}/cm^3$ and $1.2 \times 10^{20}/cm^3$, and the electron mobility is about 1.5×10^{-2} cm^2/Vs and 0.2 cm^2/Vs, respectively, for the two kinds of materials. It is concluded that the large increase in electrical conductivity of mc-Si:H over a-Si:H is almost entirely caused by an increased carrier density resulting from a high doping efficiency. The electron mobility also increases with the formation of microcrystallites, but it is also much lower than that in crystalline silicon resulting from the scattering of carriers by a high concentration of defect states and grain boundaries.

Die Elektronendichte und -beweglichkeit in P-dotierten a-Si:H- und mc-Si:H-Schichten werden mittels Leitfähigkeit und Sweep-out-Experimenten als Funktion der Meßtemperatur und Temperungstemperatur gemessen. Die Aktivierungsenergie der Leitfähigkeit wird zu 0,30 eV für a-Si:H und 0,035 eV für mc-Si:H bestimmt, mit Dotierungsniveaus von $PH_3/SiH_4 = 2\%$ bzw. 0,16%. Für beide Materialarten beträgt die Elektronendichte etwa $2{,}0 \times 10^{17}$ cm^{-3} bzw. $1{,}2 \times 10^{20}$ cm^{-3} und die Elektronenbeweglichkeit etwa $1{,}5 \times 10^{-2}$ cm^2/Vs bzw. 0,2 cm^2/Vs. Es wird angenommen, daß der hohe Anstieg der elektrischen Leitfähigkeit von mc-Si:H gegenüber a-Si:H fast vollständig durch einen Anstieg der Trägerdichte infolge einer hohen Dotierungseffizienz verursacht wird. Die Elektronenbeweglichkeit nimmt mit der Bildung von Mikrokristalliten ebenfalls zu, ist jedoch viel geringer als im kristallinen Silizium infolge der Streuung der Träger durch eine hohe Konzentration von Defektzuständen und Korngrenzen.

1. Introduction

Microcrystalline hydrogenated silicon (mc-Si:H) films have very high doping efficiency with both PH_3 and B_2H_6 and a low activation energy [1 to 7]. Such properties are suitable for the application in amorphous silicon solar cells, TFTs, and sensors. For n-type mc-Si:H films, some work which includes conductivity, field effect, thermoelectric power, and Hall effect measurements has been carried out. But many questions still remain, especially for the case of high doping levels. Crandall [8] proposed a method to measure the mobility of doped a-Si:H and Shirafuji et al. [9] applied it to undoped and lightly doped mc-Si:H. But in the case of a somewhat higher doping ratio than that used in [9], the method cannot be used because the necessary Schottky barrier device is difficult to fabricate for specimens of high conductivity because of their narrow depletion width and high tunneling current. Street et al. [10, 11] proposed a method to determine the drift mobility of P-doped a-Si:H

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using conductivity and sweep-out experiments. In this paper we derive the electron density and mobility in P-doped a-Si:H and mc-Si:H films by the same way.

2. Experimental

All of the samples in our experiments were deposited by a capacitively coupled rf glow discharge system with three separate chambers. The rf frequency was 13.56 MHz, and the base pressure was 2.5×10^{-5} Pa. Samples deposited on Corning 7059 glass and with coplanar gap Al electrodes were used to measure the electrical conductivity. Layered samples of the structure glass/Cr/i_1 a-Si:H/n^+ a-Si:H/i_2 a-Si:H/Cr and glass/Cr/i_1 a-Si:H/BF layer/n^+ mc-Si:H/i_2 a-Si:H/Cr were used to perform sweep-out measurements. The deposition conditions for each layer in the two kinds of samples were the same as those used to fabricate solar cells. A buffer layer (BF layer) was inserted between the thick intrinsic a-Si:H and the P-doped mc-Si:H layers. The BF layer consists of undoped mc-Si:H with a thickness of about 3 nm. The role of the BF layer is not only to separate the electrons in the n^+ mc-Si:H layer and the dangling bond defects in the undoped a-Si:H layer, but also to decrease the interface states at the n^+ mc-Si:H/i a-Si:H junction. Thus, the BF layer effectively prevents the electrons in the n^+ potential well from leakage through the dangling bonds in the intrinsic a-Si:H layer or the interface states by tunneling processes. The details are given in [12]. In the layered samples the thicknesses of i_1 a-Si:H, n^+ a-Si:H, n^+ mc-Si:H, and i_2 a-Si:H are 5000, 50, 30, and 50 nm, respectively. The mc-Si:H layer was deposited at a low substrate temperature of 150 °C and a high hydrogen dilution of $H_2/SiH_4 = 135$. The crystallinity of the mc-Si:H films was confirmed by Raman scattering and X-ray diffraction. The size of the microcrystallites and their volume fraction were about 7 to 10 nm and 40%, respectively. The details of the measurements and the structure properties of this mc-Si:H are given in [2]. The sweep-out experiment was performed by measuring the transient current caused by a pulse voltage at room temperature. The measurement system was controlled by a pc-computer.

3. Results and Discussion

The temperature dependence of the conductivity of the P-doped a-Si:H and mc-Si:H at a doping ratio $PH_3/SiH_4 = 2.0\%$ and 0.16%, respectively, was measured. The results showed that the activation energies were 0.30 and 0.035 eV, and the room temperature conductivity was 5.4×10^{-4} and $4.0\ \Omega^{-1}\ \mathrm{cm}^{-1}$, respectively. Spear et al. [4, 5] showed that the distance from the conduction band edge to the Fermi level vanished at doping levels higher than 1×10^3 vol ppm for P-doped mc-Si:H. Our doping ratio was just near the critical value. Therefore, we suppose that the Fermi level is very close to the conduction band edge and the temperature dependence of conductivity can be described in terms of thermionic emission over barriers produced by trapping states in the grain-boundary regions as proposed by Richter and Ley [7]. In this case the conductivity activation energy E_a corresponds to the barrier height in the grain-boundary regions. However, the tail states in a-Si:H films limit the doping efficiency and prevent the Fermi level from moving closer than 0.2 to 0.3 eV to the conduction band edge even if the doping level is very high.

We applied the sweep-out experiment to measure the electron density and mobility in the P-doped a-Si:H. We used the same doped materials as the electron source to deposit the sweep-out samples. Fig. 1 and 2 show the transient currents under different applied

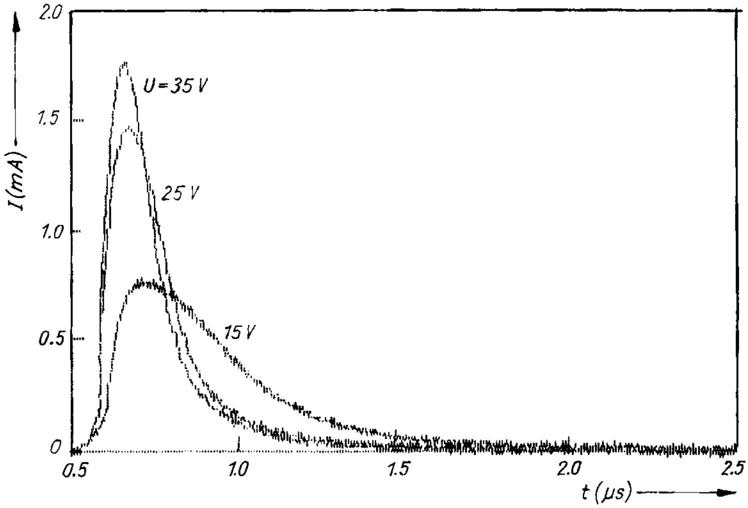

Fig. 1. Transient current responses under different applied pulse voltage for the sample with P-doped a-Si:H as the electron source

voltages and the voltage dependence of the swept-out charge by integrating the transient current. From the saturated electron charge of 4×10^{-9} C in Fig. 2 we obtained the electron density $N = 2.0 \times 10^{17}$ cm^{-3}. Combining this result with the conductivity of the same material we estimated the electron mobility to be 1.5×10^{-2} cm^2/Vs. Both of them are in agreement with the results reported by Street et al. [10, 11].

In order to measure the temperature dependence of electron density and mobility, the sweep-out experiments were performed on samples which were annealed at different temperatures for at least one hour and then quenched in cold water. At first we measured the relaxation process of the annealed and quenched sample at room temperature. Fig. 3 represents the time dependence of the swept-out charge after annealing at temperatures of 80 and 250 °C, respectively. It indicates that the measured swept-out charge shows no measurable relaxation at room temperature for up to one hour, even for annealing

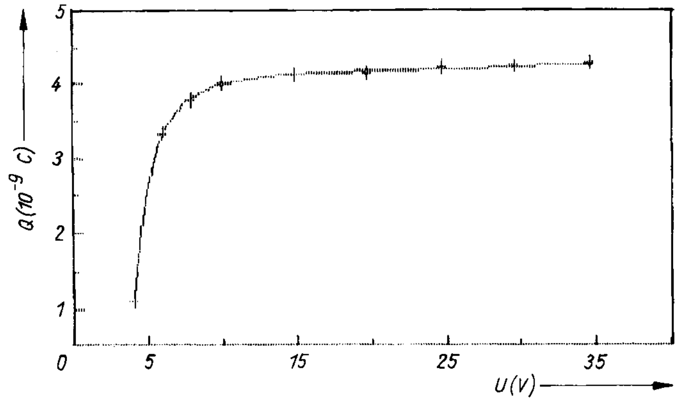

Fig. 2. Voltage dependence of swept-out charge for the sample with P-doped a-Si:H as the electron source

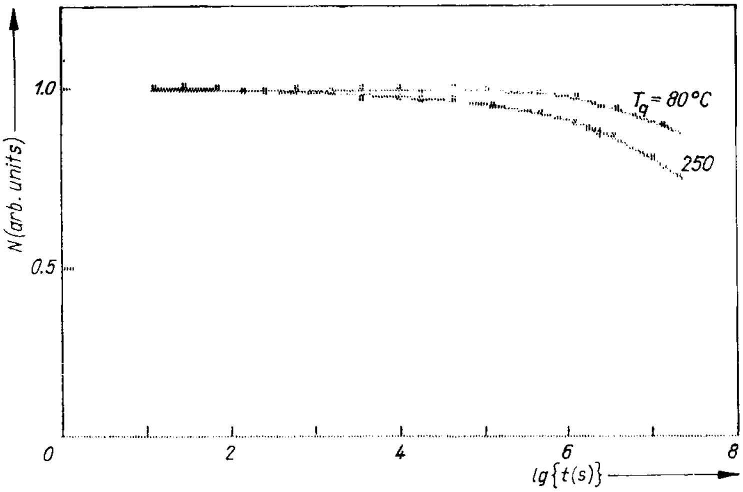

Fig. 3. Time dependence of swept-out charge concentration measured at room temperature after the sample was annealed at 80 and 250 °C and then quenched

temperatures as high as 250 °C. So we may suppose that the electron density and electron mobility measured after annealing and quenching is the same as that at the annealing temperature. Fig. 4 and 5 show the electron density and the electron mobility as a function of annealing temperature T_a. Both of them are thermally activated. The activation energies of the electron density and the mobility are 0.18 and 0.16 eV, which represent the value of $E_{av} - E_F$ and $E_c - E_{av}$, respectively. E_{av} is the energy where the distribution of trapped electrons has its maximum value, and E_F and E_c are the Fermi level and the conduction band edge, respectively. These results are also in agreement with those reported by Street et al. [10, 11]. The above examination indicates that our sweep-out measurement system is reliable.

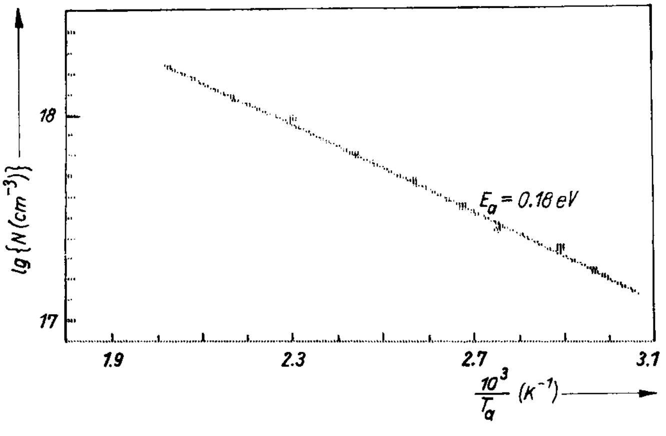

Fig. 4. Annealing temperature dependence of the electron density for the sample with P-doped a-Si:H as the electron source

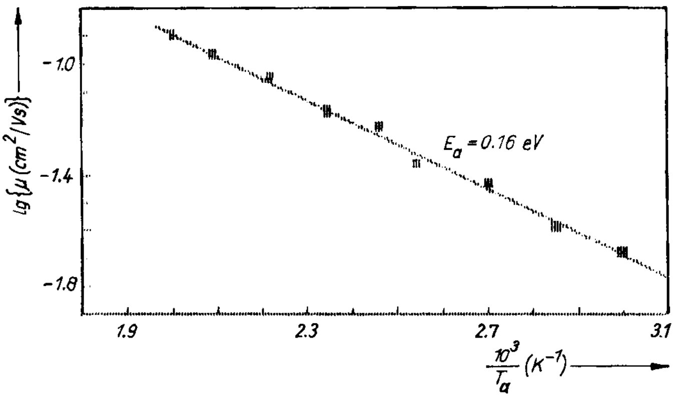

Fig. 5. Annealing temperature dependence of the electron mobility for the sample with P-doped a-Si:H as the electron source

Fig. 6 represents the sweep-out transient currents under different applied voltages for the sample with P-doped mc-Si:H as the electron source. It should be noted that the transient current has a higher value and decays over a longer time scale than that found in the sample with P-doped a-Si:H as the electron source layer. This means that the number of electrons is higher in the P-doped mc-Si:H sample than in the P-doped a-Si:H sample. Another explanation would be that under reverse pulse voltage bias the electrons must overcome the effective potential barrier at the i/n$^+$ interface to get into the thicker i layer and then be swept out. The effective barrier height E_b is dominated by the difference of the activation energies between the two kinds of materials and affected by the applied voltage. If we assume the barrier height E_b at the i a-Si:H/n$^+$ mc-Si:H interface to be 0.5 to 0.6 eV and suppose that the time scale of the current decay is limited by the thermo-emission of electrons from the n$^+$ mc-Si:H well, the release time for the electrons in the potential well is estimated to lie between 10^{-3} to 10^{-1} s according to the formula $t = w_0^{-1} \exp(E_b/kT)$,

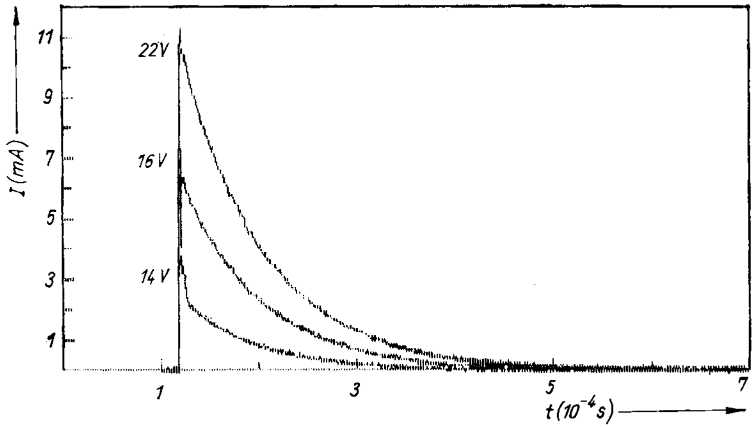

Fig. 6. Transient current responses under different applied pulse voltages for the sample with P-doped mc-Si:H as the electron source

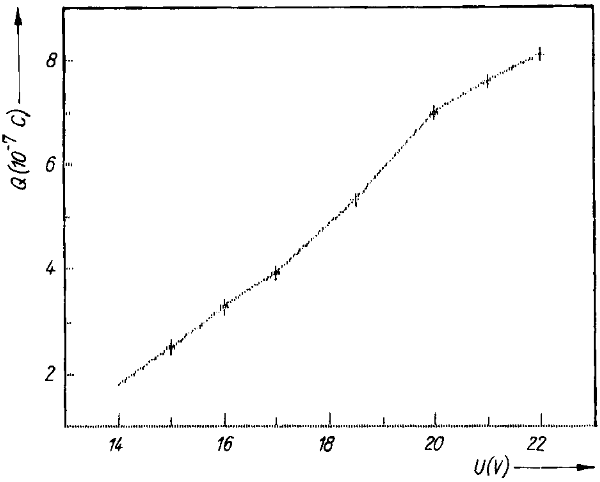

Fig. 7. Voltage dependence of the swept-out charge for the sample with P-doped mc-Si:H as the electron source

where $w_0 = 10^{11}\ \mathrm{s}^{-1}$ is the attempt-to-escape frequency, T the measurement temperature, and k the Boltzmann constant. In fact, the decay time of the sweep-out current was in the order of 10^{-3} s as shown in Fig. 6.

The voltage dependence of the swept-out charge for the sample with P-doped mc-Si:H as the electron source layer is shown in Fig. 7. It is obvious that the swept-out charge increases continuously in the range of measured voltages which implies that the electrons stored in the mc-Si:H layer cannot be totally swept out under the maximum applied voltage. However, as an estimate we chose the collected charge under the maximum applied voltage to determine a low limit for the electron density in the P-doped mc-Si:H layer and obtained a value of $1.2 \times 10^{20}\ \mathrm{cm}^{-3}$. With this electron density and the measured conductivity the room temperature electron mobility was not larger than $0.2\ \mathrm{cm}^2/\mathrm{Vs}$.

We also measured the annealing temperature T_a dependence of electron density and electron mobility for the sample with the P-doped mc-Si:H as the electron source layer and found that the electron density depends only slightly on annealing temperature. This implies that all of the electrons are in extended states, which agrees well with the conclusion reached by Spear et al. [4, 5]. Only the mobility has a thermally activated behaviour and the activation energy is about 0.03 eV. We believe that this value corresponds to the barrier height of the depleted regions between microcrystallites as supposed by Richter and Ley [7]. Therefore, we conclude that the low conductivity of mc-Si:H compared to crystalline silicon is due to the small effective mobility resulting from the scattering of carriers by a high concentration of defect states and grain boundaries.

4. Conclusion

The transport mechanism in high level P-doped amorphous and microcrystalline silicon films was studied by conductivity and sweep-out experiments. For the P-doped a-Si:H at doping level of $PH_3/SiH_4 = 2.0\%$ both electron density and mobility show a thermally activated behaviour with annealing temperature; the activation energies are 0.18 and 0.16 eV, respectively, which are in agreement with the results reported by Street et al. [10, 11]. The room temperature values of electron density and mobility are 2.0×10^{17} cm^{-3} and 1.5×10^{-2} cm^2/Vs, respectively. For the case of P-doped mc-Si:H at a doping level of $PH_3/SiH_4 = 0.16\%$ an annealing temperature independent electron density of more than 1.2×10^{20} cm^{-3} is found which means that the material is actually similar to degenerately doped crystalline silicon. The room temperature electron mobility is lower than 0.2 cm^2/Vs and the activation energy of the mobility is 0.03 eV which corresponds to the barrier height at the edge between microcrystallites.

Acknowledgements

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