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Electron mobility in nanocrystalline silicon devices

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Abstract

Electron mobility in the growth direction was measured using space charge limited current techniques in device-type *nin* structure nanocrystalline Si:H and nanocrystalline Ge:H structures. The films were grown on stainless steel foil using either hot wire or remote plasma enhanced chemical vapor deposition techniques. Grain size and crystallinity were measured using x ray and Raman spectroscopy. The size of grains in films was adjusted by changing the deposition conditions. It was found that large $\langle 220 \rangle$ grain sizes ($\sim 56\text{nm}$) could be obtained using the hot wire deposition technique, and the conductivity mobility at room temperature was measured to be $5.4\text{cm}^2/\text{Vs}$ in films with such large grains. The plasma-grown films had smaller grains and smaller mobilities. The mobility was found to increase with increasing grain size and with increasing temperature.

Keywords

Carrier mobility, Nanocrystalline materials, Thin films, Electron mobility, Thin film growth

Disciplines

Electrical and Computer Engineering

Comments

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Electron mobility in nanocrystalline silicon devices

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Electron mobility in the growth direction was measured using space charge limited current techniques in device-type *nin* structure nanocrystalline Si:H and nanocrystalline Ge:H structures. The films were grown on stainless steel foil using either hot wire or remote plasma enhanced chemical vapor deposition techniques. Grain size and crystallinity were measured using x ray and Raman spectroscopy. The size of grains in films was adjusted by changing the deposition conditions. It was found that large $\langle 220 \rangle$ grain sizes (~ 56 nm) could be obtained using the hot wire deposition technique, and the conductivity mobility at room temperature was measured to be $5.4 \text{ cm}^2/\text{V s}$ in films with such large grains. The plasma-grown films had smaller grains and smaller mobilities. The mobility was found to increase with increasing grain size and with increasing temperature. © 2006 American Institute of Physics. [DOI: 10.1063/1.2234545]

Nanocrystalline silicon (nc-Si:H) is an important material for photovoltaic devices and thin film transistors (TFT).^{1–4} An important property for device applications is the carrier mobility. Generally, the mobility is measured using Hall effect techniques,⁵ or in thin film transistor devices, using the transistor current versus gate voltage techniques.² Mobility measured using either Hall effect or TFT devices measures a transverse mobility. Also, TFT devices yield values of mobility in a surface channel, which may not be representative of the bulk layer. The mobility in TFT devices may also be representative of the best mobility, since in a material in which crystallinity is changing with thickness, the electrons may get channeled into the lowest gap state, viz., the most crystalline layer. In contrast, the performance of photovoltaic devices is dependent upon mobility in the bulk layer in the vertical or growth direction and the electrons and holes have to travel through materials with varying crystallinity. Note also that for both TFT and Hall effect measurements, the materials are grown on insulating (e.g., glass) substrates. In contrast, the photovoltaic devices are grown on conducting (e.g., steel or tin oxide) substrates.^{1,6} It is known that the substrate can have a significant influence on the morphology and structure of the subsequent film, and that the transport properties (e.g., diffusion lengths of holes) in the transverse direction may be very different from the properties in the growth direction.⁷ Therefore, it would be useful to measure the bulk conductivity mobility of carriers in the vertical or growth direction in device-type structures which are deposited on the same substrate as devices using the same growth techniques as used for photovoltaic devices. Recently, hole mobility in nc-Si:H devices was measured using time of flight techniques.⁸ In this paper, we report on a measurement of electron mobility in nanocrystalline Si:H device-type structures using a different technique.

The technique used for the measurement was space charge limited current (SCLC). The device structure was

n^+nn^+ type, with space charge injection limited to electrons. It is known from the theory of SCLC (Ref. 9) that once the current is controlled by the space charge, the current density is given by $J = 1.12\epsilon\mu V^2/L^3$, where V is the applied voltage, L is the length of the n -type layer, μ is the mobility, and ϵ is the dielectric constant. Since we know all the other parameters, the mobility can be calculated by plotting J vs V^2 .

The samples were grown using either a remote hot wire deposition technique¹⁰ or plasma growth techniques using either electron-cyclotron resonance (ECR) plasma¹¹ or VHF diode plasma.¹ Most of the devices in this work were made using the remote hot wire technique. Remote hot wire refers to the fact that unlike most hot wire depositions, in our system, the hot Ta filament is ~ 12 cm away from the substrate, thereby reducing significantly the radiant heating effect of the filament upon the substrate. In our system, the measured substrate temperature changes by only about 10–20 °C during growth. The ECR plasma chemical vapor deposition (CVD) growth system has been described previously.¹¹ All the devices were of n^+nn^+ type on stainless steel substrates, with n^+ layers being amorphous Si. Top contacts were evaporated Al films, which were annealed at 170 °C for 30 min to form good Ohmic contacts. In addition, a high current was passed before the measurement to allow Al to diffuse through any surface oxide layer. The bottom n^+ layer was 0.25 μm thick, whereas the top n^+ layer was 0.06 μm thick. The bottom layer was deliberately kept thicker so as to induce crystallinity in the nanocrystalline layer grown on it and to prevent shorts. The thickness of the nanocrystalline n layer (which was not intentionally doped but was nevertheless doped n type because of the inevitable presence of oxygen¹²) was varied between 0.5 and 1.8 μm , with most measurements done on films with n layer thicknesses of ~ 1.2 – 1.5 μm . Care was taken to induce rapid crystallinity in the nanocrystalline layer by using a very high hydrogen dilution during the initial stages of growth of this layer and then rapidly (over ~ 5 min) grading the hydrogen content down to that required for the main body of the nanocrystalline layer. If such rapid crystallization is not done, there will

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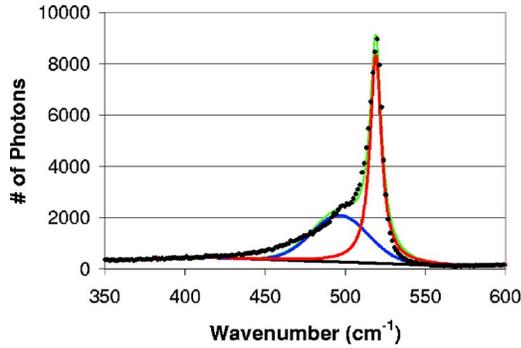


FIG. 1. (Color online) X-ray diffraction spectrum of a nc-Si n^+nm^+ structure showing a large grain size in $\langle 220 \rangle$ direction.

be a significant thickness of amorphous layer in series with a higher conductivity crystalline layer, and the mobility values will represent that of a -Si and not crystalline Si. Typical growth rates for the nanocrystalline film were $\sim 1\text{--}2 \text{ \AA/s}$. For hot wire deposited films, the initial hydrogen/silane ratio was 50:1, and the final ratio was 11.5:1. n^+ doped amorphous Si:H can be used as electron injecting contact because of the close match between the conduction bands of amorphous and crystalline Si (within 0.07 eV).¹³ The doped and undoped layers were deposited in different reactors to minimize any cross contamination induced doping of the n layer. During SCLC measurements, care was taken to not heat up the sample by using a pulse technique at the highest currents. Care was also taken to take account of the inevitable series resistance effects in probes ($\sim 0.5 \Omega$) by using four point probe techniques. Contacts were both thermally and electrically annealed to reduce the series resistance.

The structure of the films was measured using x-ray diffraction and Raman spectroscopy. Grain sizes could be changed by changing the deposition conditions, for example, growth temperatures or silane/hydrogen ratios.³ In Fig. 1, we show the x-ray spectrum of a film deposited using hot wire deposition. Both $\langle 111 \rangle$ and $\langle 220 \rangle$ grains are present, though the $\langle 220 \rangle$ grain dominates. The grain size of the $\langle 220 \rangle$ grain is quite large, 56 nm. The corresponding Raman spectrum is shown in Fig. 2, showing a high ratio (4.2:1) between the crystalline peak at 520 cm^{-1} and the amorphous shoulder at 490 cm^{-1} , implying $>80\%$ crystallinity, using the method described by Smit *et al.*¹⁴

In Fig. 3, we show the typical I vs V and I vs V^2 curve at a measurement temperature of 25°C for the sample whose Raman and x-ray spectra were shown in earlier figures. Except for the initial region, where the curve is Ohmic (the top figure), the current follows the V^2 behavior predicted for SCLC. From the slope, we deduce a mobility of $5.4 \text{ cm}^2/\text{V s}$. Using this value of mobility, from the Ohmic region, we deduce a carrier concentration of $2.5 \times 10^{14}/\text{cm}^3$ and a Fermi level position of $\sim 0.3 \text{ eV}$ below the conduction band, assuming the usual value for the effective density of states for the conduction band of Si. Note that we have shown earlier¹⁵ that nanocrystalline Si materials, at least the ones with grain sizes of $15\text{--}20 \text{ nm}$, behave very similarly to crystalline Si in p - n junction devices, and therefore, the effective density of states in nanocrystalline Si is not too dif-

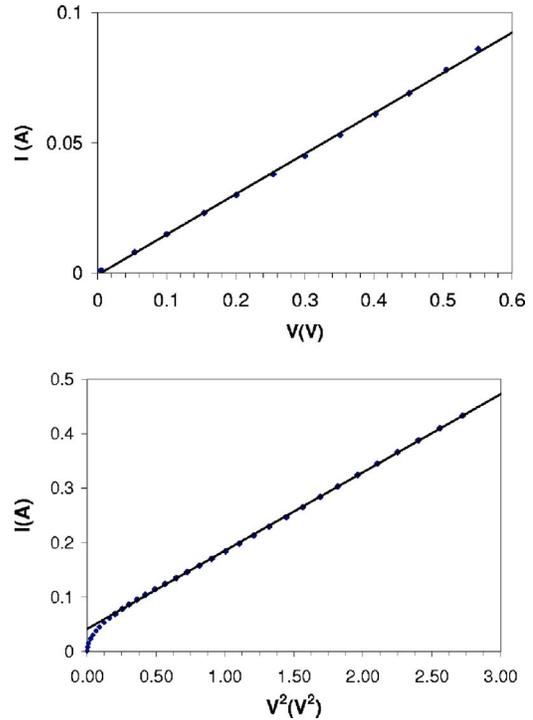


FIG. 2. (Color online) Raman spectrum of a nc-Si film with a large grain size. The ratio of crystalline to amorphous peaks is >4 , implying a crystallinity of $>80\%$.

ferent from that in crystalline Si. This is also consistent with the fact that the optical absorption coefficient of nanocrystalline Si is very close to the absorption coefficient of c -Si. From the I - V curve, the transition from Ohmic to SCLC occurs at $\sim 0.8 \text{ V}$. Using the equation for transition voltage for SCLC,⁸ $V = qN_d L^2 / \epsilon$, this voltage implies a combined trap and carrier concentration of $1.5 \times 10^{14}/\text{cm}^3$, in the same range as obtained from the Ohmic region of I - V curve. Thus, the results are self-consistent for this sample and for every sample reported here. Note that the traps are known to be about $0.35\text{--}0.5 \text{ eV}$ below the conduction band.¹⁵ Therefore, almost all the traps are filled with electrons at this temperature for this sample. Since the traps are mostly filled, we only get two regions in I - V curve, an Ohmic region and a SCLC

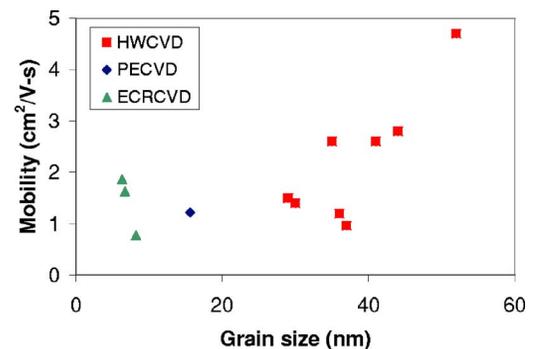


FIG. 3. (Color online) Plots of current vs voltage (top figure) and current vs square of voltage (bottom figure). The mobility is estimated from the I vs V^2 plot. The transition point in the curve indicates a changeover from Ohmic to square law behavior, and gives an estimate of the native doping in the material.

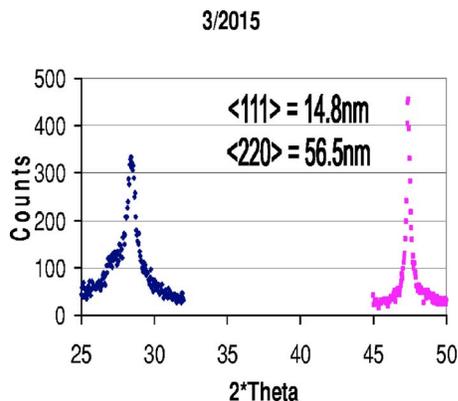


FIG. 4. (Color online) Electron mobility vs grain size for nanocrystalline Si films produced using three different techniques.

region, and not a third, almost abrupt transition region from trap controlled to trap-free limit case.⁹

In Fig. 4, we plot the mobility derived from SCLC versus the grain sizes measured using x-ray diffraction. As expected the mobility increases with grain size. Note that the mobilities in samples grown using the ECR plasma-CVD processes, the mobility values are still around or greater than 1 even though the grain sizes are very small ($\sim 8\text{--}10\text{ nm}$). This result may be due to the fact that the interfaces between layers were better in these devices, because all the layers were grown sequentially in the same reactor. Note also that the minimum electron mobility in nc-Si:H when the grains are very small is in the range of $1\text{ cm}^2/\text{V s}$, which makes sense since the generally accepted value for electron mobility in *a*-Si:H is also $\sim 1\text{ cm}^2/\text{V s}$,¹⁶ though some reports have claimed higher mobilities.¹⁷

To compare our data with mobilities measured using Hall measurements, we measured the mobility of electrons in a nc-Ge:H *nin* structure device prepared using the ECR growth technique. The grains were predominantly $\langle 220 \rangle$ oriented with a size of 22 nm. The measured electron mobility was $1.1\text{ cm}^2/\text{V s}$. This value agrees well with mobility in

nc-Ge:H films with similar grain sizes, measured using Hall effect.

Note that the mobility values measured here represent an average over thickness for the sample, because it is known that the grain sizes increase with thickness, even when one maintains the same hydrogen/silane ratios during growth. That is one of the reasons why approximately the same thickness was used for most of the samples. Note also that the effective mobility values measured using SCLC techniques represent a lower limit to the actual mobility, since any stray resistances (e.g., due to interfacial oxides) will reduce the measured mobility.

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