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Photoconductivity spectroscopy in hydrogenated microcrystalline silicon thin films

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Steady-state photoconductivity and sub-bandgap absorption measurements by the dual-beam photoconductivity (DBP) method were carried out on undoped hydrogenated microcrystalline silicon thin films prepared by VHF-PECVD and hot-wire chemical vapor deposition. The results are compared with those of the constant-photocurrent method (CPM) and photothermal deflection spectroscopy (PDS). It is found that DBP, CPM, and PDS provide complementary data on the optoelectronic processes in microcrystalline silicon.

1. Introduction

An important property of photovoltaically active μc-Si : H is the optical absorption coefficient, $\alpha(h\nu)$, especially in the sub-bandgap region. Well-established methods, such as photothermal deflection spectroscopy (PDS) [1] or transmission and reflection spectroscopy [2], have been used to measure the absolute $\alpha(h\nu)$ spectrum of a-Si : H. However, both techniques have difficulties in measuring a reliable bulk $\alpha(h\nu)$ in the lower-energy region, due to surface states and substrate absorption [3]. On the other hand, photoconductivity techniques [4–8], especially the constant-photocurrent method (CPM) [5, 6] and dual-beam photoconductivity (DBP) [7] are less affected by these problems. Thus, they have been used as alternatives in deriving $\alpha(h\nu)$ from the photoconductivity spectrum at low energies. However, the derived $\alpha(h\nu)$ in this energy range is not unique, and is affected by the occupation of the defect states due to differences in the light intensities used during the measurements. By taking this into account via model calculations, the distribution of states can be derived from a combination of, for example, CPM and PDS [8]. In this paper, we present $\alpha(h\nu)$ spectra for device-quality μc-Si : H films, measured using the DBP method at different bias light intensities. The spectra are compared with those obtained by PDS and CPM.

2. Experimental methods

Device-quality μc-Si : H films were prepared using VHF-PECVD and HW-CVD deposition systems, on glass substrates, using different silane concentrations [9, 10]. The film thicknesses were in the range 0.45–0.90 μm, and evaporated coplanar Ag electrodes 0.5 mm wide and 0.5 cm long were used. Steady-state photoconductivity, σ_{ph}, measurements were carried out using 800 and 750 nm interference filters, together with a calibrated ENH-type white light source. The applied voltage was in the ohmic region.

The dual-beam photoconductivity technique uses two light beams, a red d.c. bias light ($\lambda = 670$ nm) providing volume-generation rates from $G = 10^{15}$ to $10^{18}\,\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$, plus monochromatic a.c. light with $\sigma(h\nu) \ll G$, calibrated using a pyroelectric detector and chopped at 13 Hz. Under these conditions, the a.c. photoconductivity, $\sigma_{ph}(h\nu)$, is linear with the monochromatic light intensity and $\sigma_{ph}(G) \gg \sigma_{ph}(h\nu)$. The resulting DBP yield spectrum is finally normalized to that measured by PDS. Standard PDS and CPM measurements were carried out on the same samples, and evaluated to provide interference-free $\alpha(h\nu)$ spectra.

3. Results and discussion

σ_{ph} and the calculated $\eta\mu\tau$ product versus generation rate of the μc-Si : H films are shown in the inset of Fig. 1. The σ_{ph} values of the HW-CVD films are higher than those of the VHF-PECVD ones. The exponent γ changes from 0.5 to 0.90 (sample and history dependent), indicating that the density of defect states acting as recombination centers increases as the generation rate increases.

The direct effects of these states are detected by sub-bandgap absorption measurements. The DBP spectra, normalized to that from PDS at 1.4 eV, are shown for a HW-CVD film in Fig. 1. A good overlap exists in the $\alpha(h\nu)$ spectra obtained by the two methods between 1.2 and 1.5 eV, indicating that both techniques probe similar states. For energies below 1.2 eV, the PDS spectrum deviates from the DBP spectra, mainly due to substrate absorption. Therefore, the DBP $\alpha(h\nu)$ spectra decrease further. The difference in the $\alpha(h\nu)$ spectra from 0.6 to 1.1 eV between the low- and high-bias light DBP spectra is due to differences in the occupations of states as the

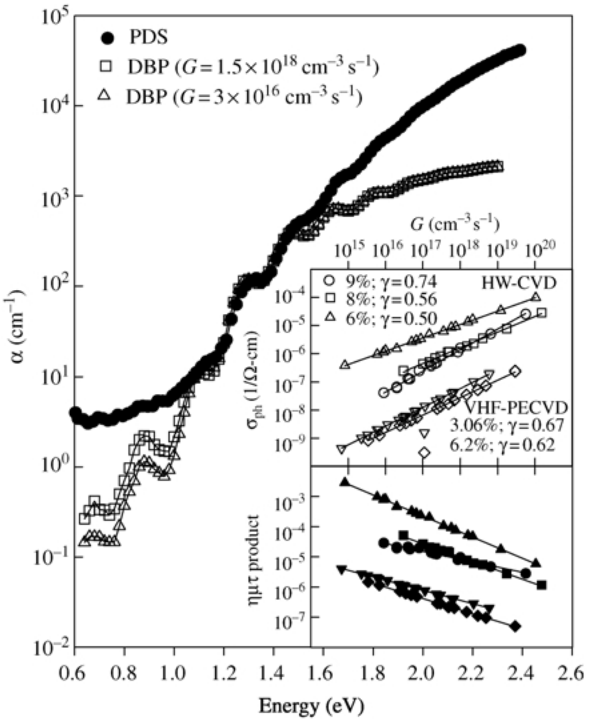

Figure 1 $\alpha(h\nu)$ spectra of a HW-CVD μc-Si : H film measured by PDS and DBP at two bias light intensities. In the inset, σ_{ph} and the $\eta\mu\tau$ products, versus generation rate, are shown for μc-Si : H films.

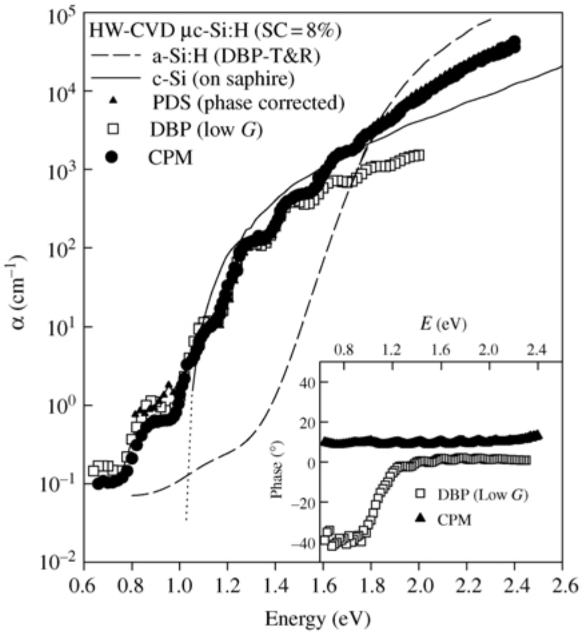

Figure 2 The $\alpha(h\nu)$ spectra of a HW-CVD μc-Si : H film, measured by PDS, CPM, and low-G DBP, and of c-Si and a-Si : H for comparison. In the inset, the phases for the CPM and DBP methods are shown. The extension with dots indicates the bandgap of c-Si, 1.12 eV.

bias light intensity changes. The magnitude of the increase in $\alpha(h\nu)$ can then be related to the distributions, densities, and capture cross sections of these states, as the generation rate due to the bias light increases. Additional information about these states can be inferred from the intensity dependence of the DBP measurements.

In addition to the DBP technique, CPM is often used to derive the $\alpha(h\nu)$ spectrum [6]. The CPM spectrum of the same film is shown in Fig. 2, together with those from DBP and PDS, corrected for substrate absorption using the phase of the PDS signal. The CPM, PDS, and the low-G DBP spectra agree very well, from 1.5 to 1.0 eV. CPM shows lower values than DBP at energies below 1.0 eV, due to a decrease in the occupation of the states, as CPM does not use d.c. bias light and is carried out with a very low generation rate from a.c. monochromatic light. When the bias light intensity is decreased further, the difference between the DBP and CPM spectra is indistinguishable (data not shown) for some samples. Similar changes in the $\alpha(h\nu)$ spectra have been observed for other samples, indicating that CPM and DBP with different bias light intensities are complementary methods to derive additional information about electronic defect states in the bandgap.

An interesting additional feature of these two techniques is the phase of the signals. As seen in the inset in Fig. 2, the phase of the CPM is almost constant for all energies. However, the phase of the DBP signal shifts below 1.2 eV. For very low generation rates, differences in the $\alpha(h\nu)$ spectra between DBP and CPM are indistinguishable, but there is a significant phase shift in the case of DBP. The only difference between the two methods is the bias light, which results in a change in the carrier dynamics.

4. Conclusions

We conclude that PDS, CPM, and the intensity dependence of DBP are complementary methods for obtaining a reliable $\alpha(h\nu)$ spectrum, and for deriving additional information about the electronic properties of μc-Si : H.

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References

1. W. B. JACKSON and N. M. AMER, *Phys. Rev. B* **25** (1982) 5559.
2. G. D. CODY, C. R. WRONSKI, B. ABELES, R. B. STEPHENS and B. BROOKS, *Sol. Cells* **2** (1980) 227.
3. S. NONOMURA, T. NISIMAKI and S. NITTA, *Philos. Mag. B* **69** (1994) 335.
4. G. MODDEL, D. A. ANDERSON and W. PAUL, *Phys. Rev. B* **22** (1980) 1918.
5. M. VANECEK, J. KOCKA, J. STUCHLIK and A. TRISKA, *Solid State Commun.* **39** (1981) 1199.
6. M. VANECEK, J. KOCKA, A. PORUBA and A. FEJFAR, *J. Appl. Phys.* **78** (1995) 6203.
7. C. R. WRONSKI, B. ABELES, T. TIEDJE and G. CODY, *Solid State Commun.* **44** (1982) 1423.
8. F. SIEBKE, H. STIEBIG and R. CARIUS, *Sol. Energy Mater. Sol. Cells* **49** (1997) 7.
9. A. L. BAIA NETO, A. LAMBERTZ, R. CARIUS and F. FINGER, *J. Non-Cryst. Solids* **299–302** (2002) 274.
10. S. KLEIN, F. FINGER, R. CARIUS, H. WAGNER and M. STUTZMANN, *Thin Solid Films* **395** (2001) 305.

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