Minority-carrier properties of microcrystalline germanium

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The ambipolar diffusion length and the minority-carrier mobility-lifetime products of microcrystalline hydrogenated germanium thin films, prepared by plasma enhanced chemical vapour deposition, are investigated by using the steady-state photocarrier technique. Different thin film samples were deposited with the dilution of the process gases, germane in hydrogen, GC = $[GeH_4]/[H_2]$, between 0.2% to 1%. The minority-carrier mobility-lifetime products are almost temperature independent. These results are consistent with a temperature-independent occupation of the negatively charged recombination centres that is determined by the Fermi level. The longest diffusion length was determined for GC = 0.2%, in agreement with earlier complementary results on sensors.

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1. Introduction

The steady-state photocarrier grating (SSPG) technique proposed by Ritter and Weiser and Ritter *et al.* [1,2] to measure the ambipolar diffusion length, L_{amb}, in semiconductors is convenient for determining the minority-carrier properties if the photocurrent is dominated by the majority-carrier current. It is thus possible to determine the minority-carrier mobility-lifetime ($\mu\tau$) product for the minority carrier from L_{amb}, in addition to the majority-carrier $\mu\tau$ product from the photocurrent. This technique complements and can be compared with other techniques like the surface photovoltage (SPV) technique [3]. Hydrogenated amorphous silicon (a-Si:H) and its alloys have been the most frequently used candidates [1-2, 4-7] for the SSPG technique. In addition, the transport properties of hydrogenated amorphous germanium (a-Ge:H) [6-7] and undoped hydrogenated microcrystalline silicon (μc-Si:H) have been studied [8-10].

In the present work, hydrogenated microcrystalline germanium (μc-Ge:H) films are the focus of our investigation. These were prepared by plasma-enhanced chemical vapour deposition (PECVD) and a variety of crystalline volume fractions. This material is considered as a good candidate for sensor applications in the detection of near-infrared radiation [11].

2. Preparation guidelines

The μc-Ge:H films were deposited by PECVD at 200°C substrate temperature in a multi-chamber deposition system at 95.7 MHz plasma excitation frequency, at a pressure of 200 mTorr and a power of 30 W. The gas flow concentrations GC = $[GeH_4/[H_2]$ were 0.2%, 0.5% and 1%. For the determination of the crystalline volume fraction, the films were characterized by Raman spectroscopy in a near-back scattering configuration with a Kr+ laser with a wavelength of 647 nm. The sample with GC = 1.0% has the highest amorphous fraction, while that with GC = 0.2% has the lowest amorphous fraction and exhibits a high degree of crystallinity [11].

A standard experimental set-up of the SSPG technique is used, which accommodates a HeNe laser (633 nm) and a cryostat to allow measurements at different temperatures. The measurement of the small signal conductivity in SSPG for the determination of L_{amb} depends on the grating period Λ which, in turn, varies as the angle of incidence of two interfering laser beams changes. The ratio $\beta = j_{coh}/j_{inc}$ is measured, where j_{coh} is the small signal current under coherent conditions with the presence of a grating and where j_{inc} is under spatially homogeneous illumination. The evaluation of the relation results in the value of L_{amb} [1, 2] and ϕ is a parameter typically between 0 and 1.

$$\beta = 1 - 2\phi\left(1 + \frac{4\pi^2 L_{amb}^2}{\Lambda^2}\right)^{-2} \tag{1}$$

The minority-carrier $\mu\tau$ product is given by

$$\mu_p \tau_p = L_{amb}^2 \frac{e}{2kT}, \tag{2}$$

where k is the Boltzmann constant and T is the absolute temperature. The subscript p denotes that holes are assumed to be the minority carriers here.

3. Results

The dark and photocurrents were measured for the three samples for complementary characterization. There was no systematic variation of the dark conductivity with GC. The sample with GC = 1% had the highest dark conductivity and a room-temperature activation energy of about 55 meV. For this sample, the SSPG experiments were not successful because the necessary sensitivity for the photocurrent under illumination could not be achieved. The activation energy of the 0.2% and 0.5% samples was between 0.14 and 0.2 eV.

Focusing on the SSPG experiments, Figs. 1 and 2 show the dependence of the photocurrent ratio β on the grating period Λ at different temperatures for the μc-Ge:H samples of GC = 0.2 and 0.5%, respectively. These successful measurements could only be achieved at temperatures below room temperature at which the dark current was reduced. There is considerable scatter in some of the data sets because of the small differences in the photosensitivity to monitor the changes when the illumination conditions were changed from the inhomogeneous illumination with the presence of the grating to the homogeneous illumination conditions.

In Figs. 1 and 2, the β values decrease with increasing grating period, as expected from Eq. (1). Here, especially at longest grating periods at which β is close to $1-2\phi$, the experimental values of β vary at different temperatures. The lines in Figs. 1 and 2 show fits with calculated β values according to Eq. (1) and with of L_{amb} and ϕ as fit parameters.

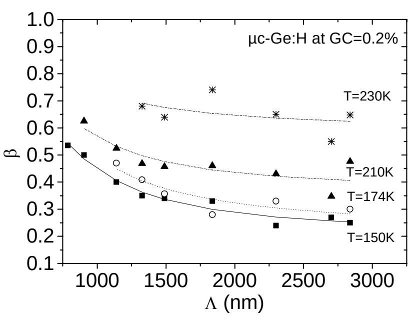

Fig. 1. The experimental (symbols) and theoretical (lines) results of β against the grating period Λ at different temperatures for the μc-Ge:H sample of GC = 0.2%.

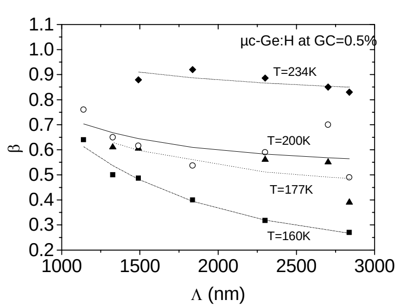

Fig. 2. Same as in Fig. 1, but for the μc-Ge:H sample of GC = 0.5%.

Fig. 3 shows the ambipolar diffusion length L_{amb} for the samples with GC= 0.2 and 0.5%. Error bars indicate the considerable error. A common feature for the two samples is that the values for L_{amb} are almost temperature independent.

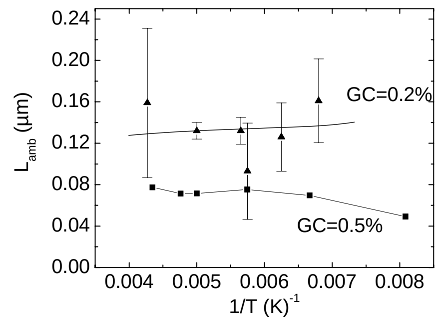

Fig. 3. The ambipolar diffusion length versus the inverse absolute temperature extracted from the best fits to the data of Figs. 1 and 2. The lines are guides to the eye.

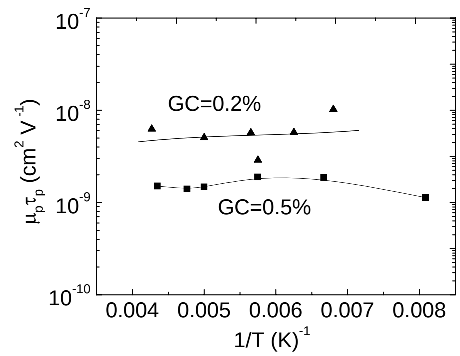

Fig. 4. The minority-carrier $\mu\tau$ products versus inverse absolute temperature for the two samples of GC = 0.5% (squares) and GC = 0.2% (triangles). The lines are guides to the eye

Fig. 4 summarizes the $\mu_p\tau_p$ products, determined from L_{amb} under the assumption that holes are the minority carriers. The T dependence of the $\mu_p\tau_p$ product is thus an image of the temperature-dependent variation of L_{amb} of Fig. 3.

4. Discussion

The three samples show a high dark conductivity and in such a case the SSPG experiment is a challenge because of the low photo- to dark- conductivity ratio which increases the error in the photocurrent detection under coherent and incoherent illumination conditions and explains the scatter in the data points in Figs. 1 and 2. Also, the fitting parameter ϕ becomes small in this case and thus the error in L_{amb} increases which is indicated by the error bars in Fig. 3. From the fact that we have deduced values for the grating quality factor close to 1, we conclude that the illumination grating is not degraded by optical scattering effects.

The minority-carrier mobility-lifetime products in Fig. 4 are almost T-independent. An explanation of this observation is based on taking the charged character of defects in the band gap into consideration. From the values of the dark-conductivity activation energies it can be concluded that almost all recombination centres or defects are negatively charged because the Fermi level is close to the conduction band edge. We note that the discussion is based on qualitative arguments without relying on a one-to-one relation between the activation energy and the Fermi level. This occupation of negatively-charged recombination-active defect states is temperature-independent so that the minority-carriers, which ”see” the negatively charged defects, have an almost temperature-independent lifetime. The relatively low values for the diffusion lengths are indicators of the background defect density. It is noted that if the mobility is temperature dependent, the lifetime may also be slightly temperature dependent in the studied relatively small temperature range

No results for the minority-carrier properties in μc-Ge:H are available in the literature. It is noted that the present results for L_{amb} are comparable to the values determined for a-Ge:H [7]. Typical diffusion lengths of high-quality microcrystalline silicon are much longer and typically > 200 nm [8,9].

In a previous sensor study [11] on μc-Ge:H based sensors prepared in a sandwich configuration, the diode with μc-Ge:H with GC=0.2% showed the best sensor properties. The present results in a coplanar geometry are consistent with those findings.

5. Conclusions

We have presented a successful study of the application of the SSPG technique to μc-Ge:H films prepared by PEVCD. The ambipolar diffusion length and the $\mu\tau$ products of the minority carriers were determined at temperatures below room temperature. The error in the values of the β parameter results from the measurement errors of the small values of the photoconductivity compared to the dark conductivity. The detrimental effect of optical scattering due to the presence of surface roughness on the photogeneration grating is minimal. The variations in the minority carrier $\mu\tau$ product, related to the ambipolar diffusion length, with temperature are small and values comparable to those for a-Ge:H have been determined. Compatible with the previous results on sensors, μc-Ge:H with GC=0.2% showed the longest diffusion length compared to other films of the series.

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