The Moving Photocarrier Grating (MPG) Technique for the Transport Properties of *a-Se:As* Films

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The moving photocarrier grating (MPG) technique for the determination of the carrier mobilities and the recombination lifetime of *a-Se:As* films has been studied. The electron and hole drift mobility and the recombination lifetime of *a-Se* films with arsenic (*As*) additions have been obtained from measurement of the short circuit current density j_{sc} as a function of grating velocity and spatial period. The hole mobility decreases due to defect density of hole traps when x exceeds 0.003, whereas the hole mobility increases for the case of low *As* addition ($x \leq 0.003$). We have found an increase in hole drift mobility and recombination lifetime, especially when *As* with ($x = 0.003$) is added into the *a-Se* film.

Keywords : *a-Se:As*, Moving photocarrier grating, Carrier mobility, Recombination lifetime

1. INTRODUCTION

Amorphous selenium (*a-Se*) has a special attraction in a wide variety of electronic device application not only because of its commercial importance as a xerographic photoreceptor material but also because of its very interesting physical properties[1,2]. While traditionally *a-Se* was employed in xerography, more recently this material has been used as the X-ray photoconductor in flat-panel X-ray image detectors[3]. The amorphous selenium film that is currently being studied for use as an X-ray photoconductor is not pure *a-Se* but rather *a-Se* alloyed with 0.2-0.5 % *As* (normally 0.3 % *As*) and doped with chlorine (*Cl*) in the 10-20 ppm range, also known as stabilized *a-Se*. A small amount of As in *a-Se* is added to enhance the thermal stability of the amorphous state.

The mobility and the recombination lifetime of electrons and holes in semiconductors are important parameters that determine the performance of many devices, such as solar cells or thin film transistors[4].

The preparation and characterization of amorphous selenium mixtures are topics of major interest both fundamentally and technologically. In order to optimize the material, a detailed knowledge of the transport parameters, i.e., electron drift mobility (μ_n), hole drift mobility (μ_p), and recombination lifetime (τ_R), is of importance. The moving photocarrier grating (MPG) technique allows us to determine μ_n, μ_p, and τ_R in semiconductors individually[5,6].

While several MPG measurements have been carried out on the transport properties of amorphous silicon (*a-Si*) sample in the past[4-6], the transport phenomena for *a-Se* films using MPG method have not been accomplished yet. We use this method to study the transport properties of $a\text{-}Se_{1-x}As_x$ films which are related with the underlying electron and hole drift mobilities and recombination lifetimes.

2. EXPERIMENT

The starting materials for *a-Se:As* films were prepared by mixing 99.999 % *a-Se* and *As* (Nippon Rare Metal Co Japan) in a weight ratio of 0.1, 0.3, 1, and 5 %. The $a-Se_{1-x}As_x$ films were deposited on the Corning glass by the thermal evaporation technique under 10^{-6} Torr. Prior to film deposition, the Corning glass was washed by ultrasonic cleaner and rinsed with deionized water and, finally blown dry in N_2 gas. The parallel gold electrodes with 1mm spatial separation were coated by thermal evaporation to measure the short circuit current flowing in *a-Se:As* films with 100 μm thickness.

The experimental setup used for the MPG measurement is shown in Fig. 1. A coherent laser beam is

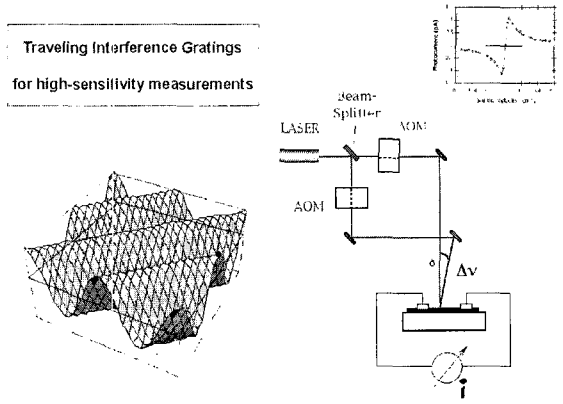

Fig. 1. Experimental set-up for the moving photo-carrier grating (MPG) measurement.

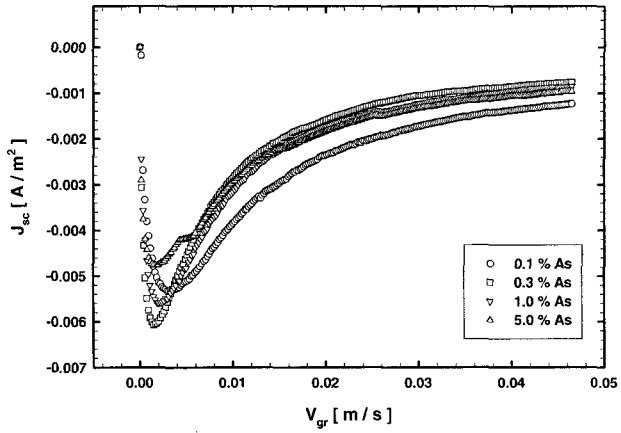

Fig. 2. Current density for different *As* addition as a function of υ_{gr}.

split into two parts using a beam splitter, which interfere at the surface of the sample under an angle δ. Thus, an intensity grating with spatial period $\Lambda = \lambda/[2\sin(\delta/2)]$ is created, where δ is the angle between the two beams and λ is the laser wavelength. Since a small frequency shift Δf is introduced between the two beams by the use of acousto-optic modulators, the resulting intensity grating pattern moves with a velocity $\upsilon_{gr} = \Lambda\Delta f$ along the sample surface. Due to their different mobilities, the photogenerated electron and hole distributions have a phase shift[7]. This implies a grating-velocity dependent short-circuit current, which makes it possible to determine independently the photocarrier mobilities and the recombination lifetime[5,7].

The light intensity at the surface of the sample (the x coordinate) has a spatial and temporal dependence[5,8]:

$$I(x,t) = (I_1 + I_2) + \sqrt{I_1 I_2}\cos[k(x - \upsilon_{gr}t)], \quad (1)$$

where I_1 and I_2 are the intensity of the two beams, and k is the spatial frequency ($k = 2\pi/\Lambda$). ω_{gr} is the angular grating velocity ($\omega_{gr} = 2\pi\upsilon_{gr}/\Lambda$). MPG measurements were performed using the line $\lambda = 532$ nm.

The resulting internal electric field produces a grating-velocity dependent short-circuit current, j_{sc}. The very existence of j_{sc} points to different mobilities of electrons and holes, and the analysis for the sign and the shape of $j_{sc}(\upsilon_{gr})$ allows the determination of the values of the carrier mobilities and their recombination lifetime. The MPG technique was applied to $a-Se_{1-x}As_x$ (x = 0.001, 0.003, 0.01, 0.05) films. The laser angles δ for *a-Se:As* films were 33.2° which gives $\Lambda = 0.93\mu m$.

3. RESULTS AND DISCUSSION

Arsenic (*As*) atoms have only five electrons in their outermost shells ($4s^2 4p^3$), while selenium (*Se*) atom have six ($4s^2 4p^4$). Arsenic presence in *Se* leaves vacancies called holes in the electron structure of *Se* atom. Therefore, *As* addition in *a-Se* film increases the hole mobility because the presence of *As* in *a-Se* film provide an accepter energy level, 0.39eV above the filled valance band. From absorption spectra using the visible spectrophotometer, the bandgap energy E_g of $a-Se_{1-x}As_x$ ($0 \le x \le 0.05$) were estimated. The energy bands of $a-Se_{1-x}As_x$ film decreased from 2.22 eV to 1.83 eV when 0.1-5 % *As* were added to *a-Se* films.

The short circuit currents measured for $a-Se_{1-x}As_x$ films as a function of υ_{gr} are plotted in Fig. 2. The short circuit currents is zero for $\upsilon_{gr} = 0$ and decreases linearly for small values of υ_{gr}. After reaching a current minimum, j_{sc} increases steadily up to the highest grating velocity used in this study. The current minimum in the MPG curves for *a-Se:As* films exhibits a different behavior when compared with curves for *a-Si:H*[7].

The inverted MPG curves of $a-Se_{1-x}As_x$, when compared with the MPG curves of *a-Si:H*, are due to the positive photocarrier charges, holes. The dominant mobility carriers are holes for *a-Se:As* films, whereas those are electrons for *a-Si:H* films[8].

The maximum short circuit current density j_{sc} (minimum current density for *a-Se*) is proportional to the laser intensity[9]. Therefore, the maximum current

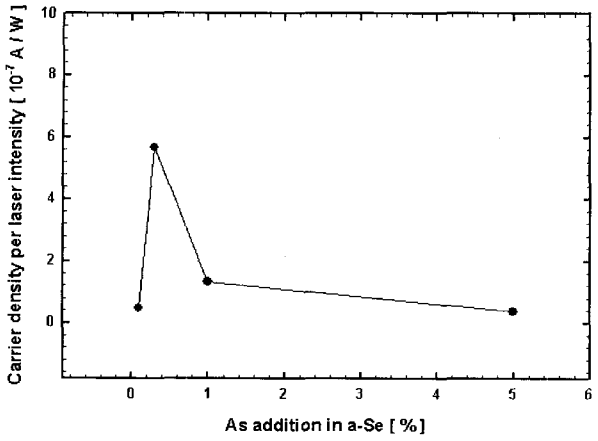

Fig. 3. Maximum current density per laser intensity as a function of *As* addition.

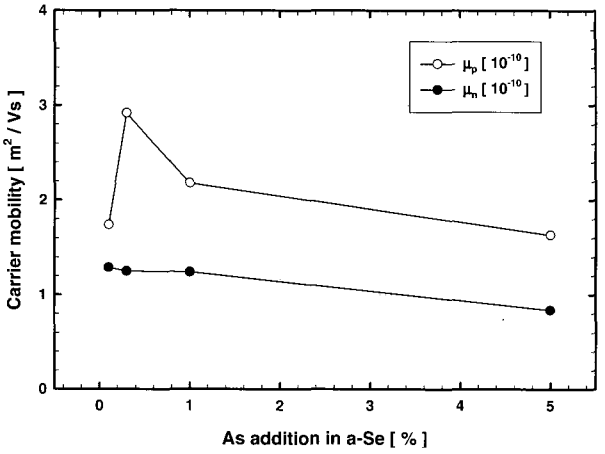

Fig. 4. The electron and hole drift mobility as a function of *As* addition.

density $j_{\max}$ with respect to laser intensity used in the measurement was obtained to determine which *As* addition is suitable for the highest photosensitivity. Figure 3 shows the maximum current densities per laser intensity, $J_{\max}/I_0$ for $a-Se_{1-x}As_x$ films as a function of *As* addition.

Our results indicate that $a-Se_{0.997}As_{0.003}$ film exhibits the best photosensitivity. The reason for this behavior is that a small amounts of *As* in the *a-Se* film increase the thermal stability and the current density due to holes, but the transport characteristic of *As* doped *a-Se* film critically deteriorates when *As* addition exceeds 0.3 %(x = 0.003), due to the defect density of the hole traps.

The carrier mobilities μ_n and μ_p are obtained by fitting the measured short circuit current to the theoretical expression derived by U. Haken et al.[5,7].

$$j_{sc}(k,\upsilon_{gr}) = \frac{c_1\upsilon_{gr}}{c_2 + c_3\upsilon_{gr}^2 + c_4\upsilon_{gr}^4}, \qquad (2)$$

where c_1, c_2, c_3, and c_4 are positive constants that depend on the transport parameters and other experimental parameters.

The electron and the hole drift mobility for $a-Se_{1-x}As_x$ films are plotted as a function of *As* addition in Fig. 4. The hole mobility decreases due to defect density of deep hole traps when x exceeds 0.003, whereas hole mobility increases for the case of low *As* addition ($x \le 0.003$) in *a-Se* films. The hole drift mobility exhibits the apparent increase at the *As* addition of x = 0.003 between x = 0.001 and x = 0.05, whereas the electron drift mobility decreases with respect to *As* addition.

In noncrystalline semiconductors like *a-Se:As* film, any photogenerated carrier in general experience multiple trapping before its recombination[5].

Thus, it seems that the space-and the time-dependent electron and hole densities include free and trapped photocarriers in *a-Se:As* films which have a high density of localized states extending from the band edges into the bandgap. According to the multiple trapping model, the drift mobility is the free carrier mobility (μ^0) reduced by the fraction of time that the carrier spends in the extended states, so that[8]

$$\mu = \mu^0 \tau_{free}/(\tau_{free} + \tau_{trap}), \qquad (3)$$

where τ_{free} is the free carrier lifetime and τ_{trap} is the time that the carrier spends in the band-tail states. The recombination lifetime is the time between excitation and recombination, given by $\tau_R = \tau_{free} + \tau_{trap}$. The addition of arsenic to the amorphous selenium changes, in principle, μ^0, τ_{free}, τ_{trap} simultaneously, so the three parameters can contribute to the decrease of μ_n and μ_p. The free carrier mobility of amorphous materials is limited by the scattering of free carriers due to the intrinsic disorder of the amorphous structure[10]. It seems that high *As* addition ($x \ge 0.003$) in *a-Se* films leads to an increase in the amount of structural disorder.

The dependence of the recombination lifetime τ_R from MPG techniques is also shown in Fig. 5. We have found that τ_R increases up to 0.3 % *As* addition and decreases thereafter. The $a-Se_{0.997}As_{0.003}$(0.3 %*As*) film also exhibits an apparent increase in recombination lifetime. We assign this change to the contribution of two factors. On the other hand, a small additions of *As* in

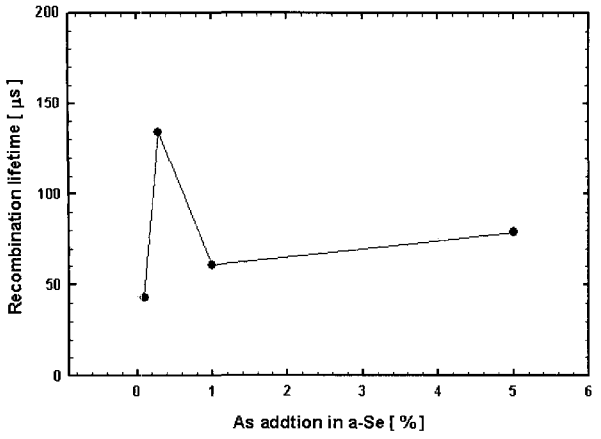

Fig. 5. The recombination lifetimes for *a-Se:As* films as a function of *As* addition.

the *a-Se* films up to x = 0.003 enhance the electric conductivity of $a-Se_{1-x}As_x$ films, while further *As* addition induces the undesirable deep hole traps in *a-Se* samples[3]. It seems that the increase of τ_R at 5 % *As* addition ($x = 0.05$) is due to high defect density of deep hole traps. There is a correation between the hole drift mobility and the Urbach energy[8].

Although less affected by the disorder than the valance-band tail, the conduction-band tail width is also expected to increase with respect to arsenic content. The presence of deeper traps increases the re-excitation time of carriers and decreases the drift mobility. The dependence of τ_R on *As* addition shown in Fig. 5 can be explained as the contribution to two factors. On the other hands, the density of mid-gap states that act as recombination centers increases with arsenic content. An increase in the conduction-and valance-band widths leads to the presence of deeper electron and hole traps, which increases the recombination lifetime in 5 % *As* added *a-Se* film.

4. CONCLUSION

The electron and hole drift mobility and the recombination lifetime of *a-Se* films with *As* additions have been obtained from MPG measurement. The hole drift mobility and the recombination lifetime exhibit the apparent increase at the *As* addition of x = 0.003 between x = 0.001 and x = 0.05, whereas the electron drift mobility decreases with respect to *As* addition.

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