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AMORPHOUS, VITREOUS, AND POROUS SEMICONDUCTORS

The Density of States in the Mobility Gap of Amorphous Hydrogenated Silicon Doped with Erbium

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Abstract—The effect of doping films of amorphous hydrogenated silicon (*a*-Si:H) with erbium on the density of the states in the mobility gap is studied. The data obtained are compared with those for *a*-Si:H films doped with arsenic. The data on the density of the states in the lower and upper halves of the mobility gap are determined from measurements of the spectral dependences of the absorption coefficient and the temperature dependences of the constant and modulated components of the photoconductivity in films exposed to modulated light, respectively. It is shown that doping the *a*-Si:H films with erbium leads to an increase in the density of states both in the lower and upper halves of the mobility gap. *© 2005 Pleiades Publishing, Inc.*

Films of amorphous hydrogenated silicon doped with erbium *a*-Si:H(Er) attract the attention of researchers in connection with the fact that an intense photoluminescence and electroluminescence with an emission peak at a wavelength of 1.54 μm, which corresponds to a minimum of losses in a quartz optical fiber, is observed in them. The luminescence of Er^{3+} erbium ions in *a*-Si:H is much more intense and its thermal quenching is much less pronounced than in the case of Er^{3+} luminescence in crystalline Si [1, 2].

In the majority of the earlier publications concerned with studying the *a*-Si:H(Er) films, the photoluminescence of this material was analyzed (see, for example, [2]). It was shown that the luminescence intensity depended on the concentrations of the oxygen and erbium atoms introduced into *a*-Si:H and attained a maximum at an erbium concentration of $N_{\mathrm{Er}} \approx 10^{20}$ cm^{-3} [3]. However, there is hardly any data concerning the effect of doping *a*-Si:H with erbium on the density of the localized electronic states in this material in the available publications. At the same time, the optical and photoelectric properties of *a*-Si:H(Er) would seem to depend, to a great extent, on the distribution of the density of the electronic states in the mobility gap. Therefore, we performed optical and photoelectric studies of the *a*-Si:H(Er) films and obtained information about the effect of doping *a*-Si:H with Er on the density of its localized electronic states; in addition, we compared the results obtained with the data on films doped with a traditional impurity (As).

In this study, we investigated *a*-Si:H(Er) films obtained by a decomposition of monosilane (SiH_4) in a high-frequency glow discharge. Films with a thickness of ~0.8 μm were deposited onto a quartz substrate at a temperature of 250°C. The films were then doped with erbium using a sublimation of the metal–organic compound $Er(C_5H_7O_2)_3$ at various temperatures T_f (90, 95, and 105°C). The compound was installed in a vacuum channel connected to the reaction chamber. According to the results of measurements of the Rutherford backscattering, the concentration of introduced erbium increased from 2×10^{19} to 3.3×10^{19} cm^{-3} as T_f was increased. Photoluminescence at a wavelength of 1.54 μm was observed in the obtained films. The films exhibited an *n*-type conductivity, and the Fermi level was located below the conduction-band bottom at a depth of $E_C - E_F = 0.34$–0.36 eV at room temperature. The value of $E_C - E_F$ was determined from the expression $E_C - E_F = kT\ln(\sigma_0/\sigma_d)$, where σ_d is the dark electrical conductivity and $\sigma_0 = 150\ \Omega^{-1}$ cm^{-1} is the lowest metallic conductivity [4].

The *a*-Si:H(As) films with the Fermi level position $E_C - E_F = 0.34$ eV were obtained as a result of introducing arsine (AsH_3) into the reaction chamber. The volume ratio of the gases was $[AsH_3]/[SiH_4] = 10^{-5}$. All the measurements were performed in vacuum with a residual pressure of 10^{-3} Pa after annealing the samples for 30 min at $T = 180$°C.

In order to gain insight into the effect of doping *a*-Si:H with Er on the density of the states in the lower half of the mobility gap, we measured the spectral dependences of the absorption coefficient α using the constant-photocurrent method [5]. The distribution of the density of the states, $N_t(E)$, in the upper half of the mobility gap was determined from measurements of the temperature dependences of the conductivity in the case where the films were exposed to light with the fre-

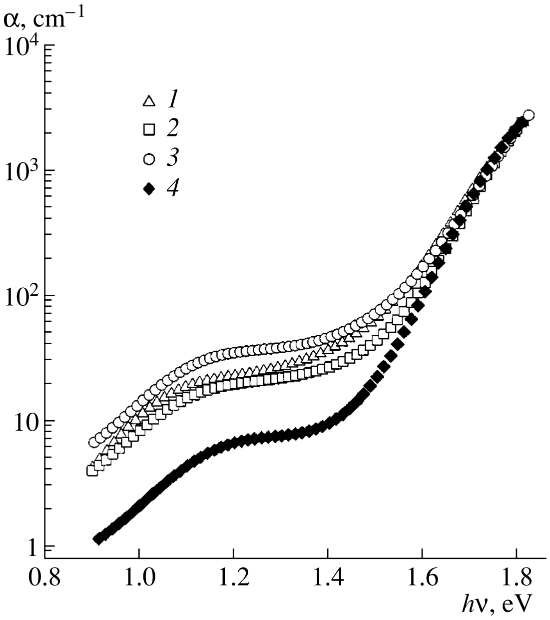

Fig. 1. Spectral dependences of the absorption coefficient α for the (*1*–*3*) *a*-Si:H(Er) films and (*4*) *a*-Si:H(As) films. The sublimation temperature during the process of doping with erbium was T_f = (*1*) 90, (*2*) 95, and (*3*) 105°C.

quency ω. According to [6], the distribution $N_t(E)$ can be determined from measurements of the constant and alternating components of the photocurrent. In this case,

$$N_t(E_F^n) = \frac{G}{\omega kT}\frac{\Delta\bar{\sigma}}{\Delta\tilde{\sigma}},$$

where $\Delta\bar{\sigma}$ and $\Delta\tilde{\sigma}$ are the photocurrent's constant component and the amplitude of the alternating component, respectively; E_F^n is the position of the quasi-Fermi level for electrons; and *G* is the amplitude of the generation rate for nonequilibrium charge carriers under modulated excitation. By varying the temperature or the excitation intensity, we can vary the position E_F^n and, correspondingly, determine the distribution $N_t(E)$ from the measurements of $\Delta\bar{\sigma}$ and $\Delta\tilde{\sigma}$. The above expression for $N_t(E_F^n)$ is valid for the range of modulation frequencies that satisfy the condition

$$\frac{1}{\tau_n} < \omega < N_C^* vS\exp[-(E_C - E_F^n)/kT],$$

where τ_n, N_C^*, v, and *S* are the characteristic photoresponse time; the effective density of the states in the conduction band; the thermal velocity of the charge carriers; and the cross section of the charge-carrier capture by localized states, respectively. The upper restriction imposed on the value of ω is necessary to ensure thermodynamic equilibrium between the free charge carriers and the charge carriers captured by the states in the vicinity of E_F^n in the case of modulated excitation. At the same time, under a condition in which the value of ω is limited from below, the value of $\Delta\tilde{\sigma}$ should not depend on the lifetime of the charge carriers and should vary in inverse proportion to ω.

The quantities $\Delta\bar{\sigma}$ and $\Delta\tilde{\sigma}$ were measured under the exposure of the films to modulated light from a light-emitting diode with the photon energy 1.85 eV and the amplitude of the modulated incident-photon flux $I = 9.6 \times 10^{13}$ cm^{-2} s^{-1}. The modulation frequency was $f = \omega/2\pi = 2$ kHz. Measurements of the frequency dependences of $\Delta\tilde{\sigma}$ for the films under study showed that this modulation frequency satisfied the above condition for the determination of $N_t(E)$ from the measurements of $\Delta\bar{\sigma}$ and $\Delta\tilde{\sigma}$.

In Fig. 1, we show the spectral dependences of the absorption coefficient α for the studied *a*-Si:H(Er) films. In order to aid comparison, the spectral dependence of α for *a*-Si:H(As) is also shown in Fig. 1. As can be seen, the value of α for the films doped with erbium exceeds that for the films doped with arsenic by nearly an order of magnitude in the region where radiation is absorbed by the structure defects in *a*-Si:H ($h\nu < 1.5$ eV). It is noteworthy that a certain increase in the absorption by defects is observed as the value of T_f (and, correspondingly, the concentration of erbium atoms introduced into *a*-Si:H) increases.

It is well known that the concentration of the defects (of a dangling-bond type) in the *a*-Si:H films depends on the position of the Fermi level in the mobility gap [7]. In the *a*-Si:H(Er) and *a*-Si:H(As) films studied by us, the positions of the Fermi levels were close to each other. Therefore, the larger absorption in the region corresponding to the defect states for *a*-Si:H(Er) indicates that the introduction of Er into *a*-Si:H gives rise to a higher concentration of defects than in the case of doping *a*-Si:H films with arsenic. This behavior can be related to the fact that, according to the available data [8], the Er atoms are incorporated into the *a*-Si:H structure as the ErO_x becomes more complex. Correspondingly, the introduction of Er into *a*-Si:H can lead to a larger increase in the density of the defect states located in the middle of the mobility gap than in the case of traditional impurities.

In Fig. 2, we show the temperature dependences of the constant photoconductivity component and the amplitude of the alternating component of the conductivity as obtained for the studied *a*-Si:H films. It can be seen that the amplitude of the alternating component of the photoconductivity is smaller than the constant component by two orders of magnitude. This behavior is related to the long characteristic photoresponse time of these films.

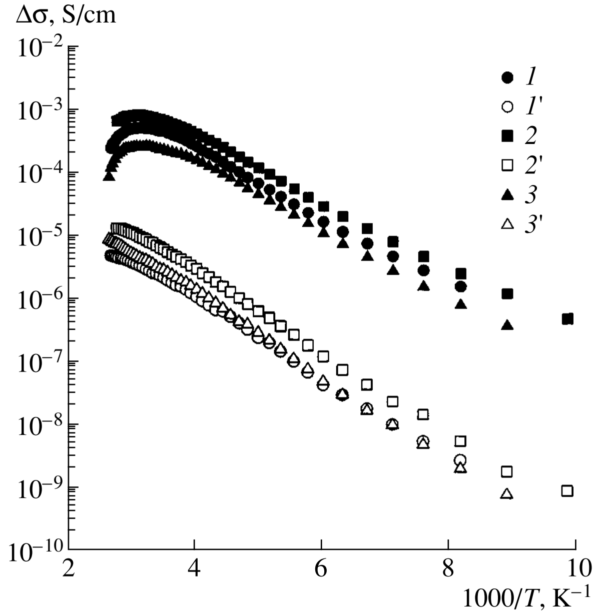

Fig. 2. Temperature dependences of the photoconductivity's constant component $\Delta\bar{\sigma}$ (curves *1–3*) and the amplitudes of the alternating component of the conductivity $\Delta\tilde{\sigma}$ (curves *1'–3'*) for the *a*-Si:H(Er) films obtained at T_f = (*1, 1'*) 95 or (*2, 2'*) 105°C, and (*3, 3'*) for the *a*-Si:H(As) film.

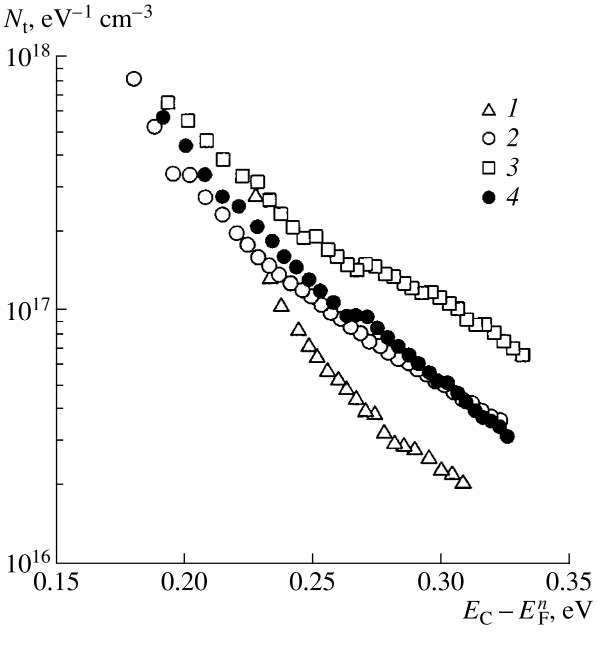

Fig. 3. Distribution of the density of the states N_t in the vicinity of the conduction-band bottom for the (*1–3*) *a*-Si:H(Er) films and (*4*) *a*-Si:H(As) films. The numbers at curves *1–3* correspond to those in Fig. 1.

The distribution of the density of the electronic states in the upper half of the mobility gap for the studied *a*-Si:H films doped with Er or As was determined from processing the temperature dependences of $\Delta\bar{\sigma}$ and $\Delta\tilde{\sigma}$ (see Fig. 3). The values of $E_C - E_F^n$ were determined from the expression

$$E_C - E_F^n = kT\ln(\sigma_0/\Delta\bar{\sigma}).$$

It can be seen in Fig. 3, by comparing the data obtained for the *a*-Si:H(Er) and *a*-Si:H(As) films, that the density of the states in the upper half of the mobility gap for the *a*-Si:H film doped with As is close to $N_t(E)$ for the *a*-Si:H film doped with Er at T_f = 95°C. It can also be seen from Fig. 3 that the density of the electronic states near the conduction-band bottom increases as T_f (and, correspondingly, the concentration of Er atoms introduced into *a*-Si) increases. We can note that the obtained result makes it possible to account for the different dynamics of the variation in the electrical conductivity under a prolonged illumination of *a*-Si:H films that have experienced various levels of doping with erbium [9]. A decrease in the relative variation in the electrical conductivity of *a*-Si:H(Er) films as the Er concentration increases under their exposure to prolonged illumination can be related to an increase in the density of the states in the region in which the shift of the Fermi level occurs.

Thus, the studies performed by us showed that the doping of *a*-Si:H films with Er led to a large increase in the density of the states in the mobility gap of this material as compared to *a*-Si:H doped with traditional donor impurities.

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