Effect of surface recombination on photoelectric emission from semiconductors with a negative electron affinity

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The rate of surface recombination, S, on GaAs and InGaAsP with a negative electron affinity reaches $\sim 10^6$ cm/s and has a strong effect on the quantum yield of photoemission. Analysis shows that the large values of S are determined in part by the diffuse reflection of electrons from the surface.

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The emission of photoelectrons from semiconductors into vacuum is such a fast process ($\tau \leqslant 10^{-14}$ s) that surface recombination is usually ignored in analyzing the effect.[1] It is suggested in Refs. 2 and 3 that surface recombination might affect the quantum yield of photoemission in the case of semiconductors with a negative electron affinity. In the present letter we report the first study of the surface-recombination rate S on semiconductors with a negative electron affinity and the effect of this recombination on the quantum yield of the photoemission from such semiconductors.

The experiments were carried out in ultrahigh vacuum ($p \sim 10^{-10}$ Torr) with p-type epitaxial films of GaAs and InGaAsP ($E_g = 1.7$ eV) doped with zinc to a concentration of about 5×10^{18} cm^{-3}. The samples were purified by heating in ultrahigh vacuum and activated with cesium and oxygen until a negative electron affinity and a maximum photoemission were achieved.[2,4] The rate of surface recombiantion was measured by a cathodoluminescence method.[5] This method involves measuring the cathodoluminescence intensity I_L vs the energy of the incident electrons, ε. The surface recombination rate is found by comparing the experimental $I_L(\varepsilon)$ characteristics with the theoretical characteristics found from the solution of the diffusion equation for nonequilibrium electrons with boundary conditions containing S (Ref. 5):

$$D \left.\frac{dn(x)}{dx}\right|_{x=d} = Sn(x)\Big|_{x=d} \qquad (1)$$

$$n \to 0 \quad \text{as} \quad x \to \infty$$

Here D is the diffusion coefficient for the minority carriers, $n(x)$ is the electron concentration, and d is the width of the space-charge region.

The experimental results are shown in Fig. 1 as a plot of the photoemission quantum yield vs the surface recombination rate, for GaAs ($\lambda = 0.8\ \mu$m) and InGaAsP ($\lambda = 1\ \mu$m) with a negative electron affinity. The experimental points correspond to different GaAs and InGaAsP samples, which differ in surface recombination rate. We see that for these particular samples there is a clear correlation between the surface

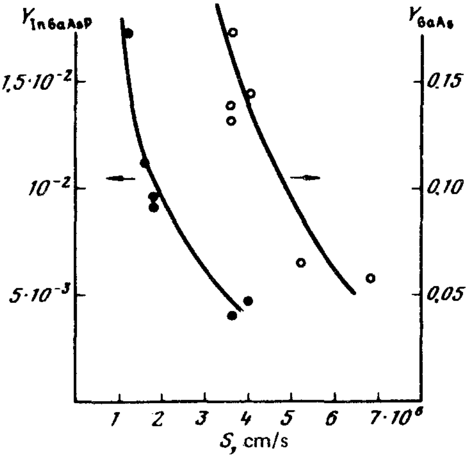

FIG. 1. Photoemission quantum yield vs the surface recombination rate for GaAs ($\lambda = 0.8$ μm) and InGaAsP ($\lambda = 1$ μm) with a negative electron affinity.

recombination rate and the photoemission quantum yield. An increase in the surface recombination rate leads to a decrease in the photoemission quantum yield.

It can be seen from Fig. 1 that the surface recombination rates on these samples are extremely high, $(1\text{–}7)\times10^6$ cm/s, close to the maximum possible value for these semiconductors ($S_{\max} = \bar{v}_T/4 = 1\times10^7$ cm/s, where $\bar{v}_T$ is the average thermal velocity of the electrons). Which properties of the semiconductor's surface are responsible for this high rate of surface recombination, and how do these properties affect the photoemission effectiveness? First we note that, as follows from (1), the measured surface recombination rate pertains not to the surface of the semiconductor but to the boundary of the space-charge region, which is related to the surface band curvature (the bands are curved downward); i.e., this is an effective surface recombination rate. Consequently, the value of S is determined not only by the capture cross section and the surface-state density but also by the transport of electrons through the space-charge region.

In the strong electric field of the space-charge region the energy of the electrons increases sharply, reaching the value of the band curvature ($v_B \approx 0.5$ eV). We can therefore ignore the scattering of electrons by ionized impurities in the space-charge region, despite the high concentration of these impurities; the primary mechanism for electron scattering in this region is then scattering by polar optical phonons. The mean free path for hot electrons in GaAs and InGaAsP for scattering by polar optical photons is[3] $p_{p0} \gtrsim 700$ Å, much larger than the width of the space-charge region at the given doping level. The electrons thus cross the space-charge region without being scattered and without undergoing recombination ($L_{\text{diff}} \gtrsim 1$ μm), and the current of electrons in the space-charge region may be thought of as the sum of two currents: the forward current and that reflected from the surface. Only those electrons which undergo specular reflection from the surface retain a normal momentum component large enough to overcome the electric field and to reach the boundary of the space-charge region. According to the kinetic theory, the current density of electrons in the space-charge region near its boundary with the interior of the semiconductor is

$$j_1 = \frac{1}{4}\,\bar{v}_{\mathrm{T}}\,n(d) - \frac{1}{4}\,\bar{v}_{\mathrm{T}}n(d)R_m = \frac{1}{4}\,\bar{v}_{\mathrm{T}}n(d)\,(1-R_m), \tag{2}$$

where $n(d)$ is the electron concentration at the boundary of the space-charge region, and R_m is the specular reflection coefficient of the surface for electrons. The current density j_1 is equal to the diffusion flux density in the interior of the semiconductor near the boundary of the space-charge region:

$$j_1 = \frac{1}{4}\,\bar{v}_{\mathrm{T}}\,n(d)\,(1-R_m) = D\,\frac{dn(x)}{dx}\bigg|_{x=d} \tag{3}$$

Comparing (1) and (3), we find

$$S = \frac{1}{4}\,\bar{v}_{\mathrm{T}}\,(1-R_m)\,; \tag{4}$$

i.e., the surface recombination rate is determined by the specular reflection coefficient of the surface for electrons, R_m.

Analysis of the experimental results in view of (4) shows that for GaAs photocathodes the value of R_m lies in the range 0.3–0.65, while for InGaAsP we find $R_m = 0.6$–0.9; i.e., the reflection of electrons from the surface is partially diffuse. The electrons which are reflected diffusely from the surface cannot escape from the potential well in the band-curvature region, and they ultimately recombine. The high surface recombination rates which we measured on the heavily doped *p*-type GaAs and InGaAsP semiconductors are therefore linked to the presence near the surface of a potential well for electrons (a band-curvature region) and the partially diffuse nature of the electron reflection from the surface.

Finally, we consider how an increase in the diffuse reflection of electrons from the surface, which increase the effective surface recombination rate, can cause a decrease in the quantum yield of photoemission. According to Ref. 3, the transmission of a semiconductor-vacuum interface is low even for electrons with energies above the potential barrier, and most of the electrons escape into vacuum only after repeatedly crossing the band-curvature region. An increase in the diffuse reflection from the surface has the consequence that the electrons lose their normal momentum component more rapidly and drop below the vacuum level.

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[1] A. H. Sommer, Photoemissive Materials, Wiley, New York, 1978 (Russ. transl. Energiya, Moscow, 1978).
[2] R. L. Bell, Negative Electron Affinity Devices, Oxford Univ. Press, 1973 (Russ. transl. Energiya, Moscow, 1978).
[3] A. L. Musatov and V. L. Korotkikh, Izv. Akad. Nauk SSSR, Ser. Fiz. **46**, 1357 (1982).
[4] A. L. Musatov, V. M. Turchinskiĭ, A. V. Lebedev, and L. E. Yatsenko, Radioteckh. Elektron. **26**, 2421 (1981).
[5] A. D. Korinfskiĭ and A. L. Musatov, Prib. Tekh. Eksp. No. 1, 163 (1983).

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