LOCAL CATHODOLUMINESCENCE OF GRADED-GAP SEMICONDUCTORS

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An expression is obtained for the spatial distribution of nonequilibrium carriers in a graded-gap semiconductor excited by a focused electron probe. Comparison between calculated and experimental spectra is used to estimate the diffusion length and the reduced surface recombination rate.

Luminescence monitoring of the parameters of graded-gap semiconductors is attracting considerable interest because of their applications in semiconductor devices [12].

The drift-diffusion displacement of nonequilibrium minority carriers within a graded-gap semiconductor under the influence of the built-in quasielectric field $\mathcal{E}$ is due to the band-gap gradient $(\vec{\mathcal{E}} = -(1/e)\,\mathrm{grad}\,E_g)$ and significantly modifies the spectrum of recombination radiation, leading to an expansion of the emission band toward longer wavelength. This effect can be seen experimentally in the electroluminescence [3] and photoluminescence [4] of the variable-composition solid solutions $Al_xGa_{x-1}As$. It was shown in [5] that comparison of calculated and experimental photoluminescence spectra of graded-gap semiconductors can be used to determine the diffusion length and the rate of surface recombination of minority carriers. This was done by solving the one-dimensional diffusion equation, and an expression was obtained for the long-wave part of the spectrum. The luminescence was excited and recorded from the wide-gap side of the samples, prepared by the cross-cut technique.

In this paper, we solve the problem of the three-dimensional distribution of minority carriers in a graded-gap semiconductor, excited by a focused electron beam, and calculate the long-wave decrease in the cathodoluminescence spectrum. The recombination parameters are determined by fitting the calculated curves to the experimental spectrum. The spectra are recorded directly from the exposed sides of the specimen, excited by the focused electron beam, so that there is no need for special preparation of the samples.

Suppose that the electron beam is incident on the surface of a semi-infinite, graded-gap semiconductor in which the band gap varies linearly with depth (grad E_g = const). The origin of coordinates will be placed at the point at which the electron beam cuts the surface, the Ox axis is parallel to the built-in quasi-electric field $\mathcal{E}$, and the Oz axis is parallel to the electron beam, pointing into the sample.

The distribution of minority carriers is described by the time-independent diffusion equation

$$\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}+\frac{\partial^2 p}{\partial z^2}-2a\frac{\partial p}{\partial x}-\frac{p}{L^2}+\frac{g(x,\ y,\ z)}{D}=0, \qquad (1)$$

where p is the concentration of nonequilibrium minority carriers (holes), $\alpha = e\mathcal{E}/(2kT)$, L and D are, respectively, the diffusion length and the hole diffusion coefficient, and g is the generation function. The boundary conditions for (1) are: $D(\partial p/\partial z)_{z=0}=Sp_{z=0}$, where S is the rate of surface recombination.

Using Green's function method to integrate (1), we find the solution in the form

$$p(x,\ y,\ z)=e^{ax}\int_{-\infty}^{\infty}d\xi\int_{-\infty}^{\infty}d\eta\int_{0}^{\infty}\frac{g(\xi,\ \eta,\zeta)}{D}e^{-a\xi}G(x,\ y,\ z;\ \xi,\ \eta,\ \zeta)\,d\zeta.$$

where x, y, z and ξ, η, ζ are the coordinates of the points of observation and of the sources, respectively, and G is Green's function, given by

$$G(x,\ y,\ z;\ \xi,\ \eta,\ \zeta)=\frac{\exp\left[-\varkappa\sqrt{(x-\xi)^2+(y-\eta)^2+(z-\zeta)^2}\right]}{4\pi\sqrt{(x-\xi)^2+(y-\eta)^2+(z-\zeta)^2}}+$$
$$+\frac{\exp\left[-\varkappa\sqrt{(x-\xi)^2+(y-\eta)^2+(z+\zeta)^2}\right]}{4\pi\sqrt{(x-\xi)^2+(y-\eta)^2+(z+\zeta)^2}}-$$
$$-\frac{h}{2\pi}\int_{\zeta}^{\infty}\frac{\exp h(\zeta-t)\exp\left[-\varkappa\sqrt{(x-\xi)^2+(y-\eta)^2+(z+t)^2}\right]}{\sqrt{(x-\xi)^2+(y-\eta)^2+(z+t)^2}}dt,$$

where $\varkappa^2=a^2+1/L^2$ and h = S/D is the reduced rate of surface recombination. We note that the above expression for Green's function is identical for $\alpha = 0$ with the expression found in [5] for uniform-gap semiconductors.

For low levels of excitation, for which intergap recombination can take place, the cathodoluminescence intensity I(x) is given by

$$I(x)=(1/\tau_r)\int p(x,\ y,\ z)dydz, \qquad (2)$$

where τ_r is the radiative lifetime of minority carriers and we have neglected the change in recombination conditions in the surface layer [6]. Since the energy of the radiated photons is $h\nu(x)=E_g(x)$, we find that, if the band gap is a linear function of position, i.e., $dE_g/dx=e\mathcal{E}$, we have

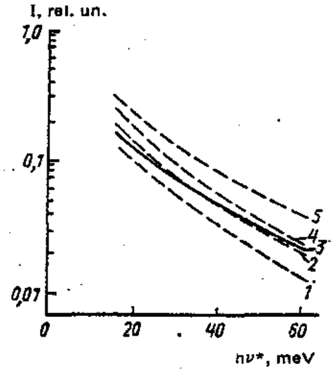
$$x=h\nu^*/(e\mathcal{E}), \qquad (3)$$

where the energy hν* is measured from the value of E_g at the point of incidence of the electron beam $(h\nu^*=h\nu(x)-E_g(0))$. Consequently, substituting (3) into the above expression, we can transform from the spatial distribution of intensity, given by (2), to the energy distribution, i.e., the cathodoluminescence spectrum

$$I(h\nu^*/e\mathcal{E})=(1/\tau_r)\int p(h\nu^*/e\mathcal{E},\ y,\ z)dydz.$$

Thus, knowing the distribution p(x, y, z) of the nonequilibrium carriers, and assuming that h and κ are parameters whereas α and $\mathcal{E}$ are known, we can compute a family of curves describing the long-wave part of the spectrum and then compare them with experimental spectra in order to determine the reduced rate of surface recombination S/D and the diffusion length L of minority carriers.

The theoretical spectra were computed for a point source. The experimental



Long-wave decrease of experimental and calculated cathodoluminescence spectra at 80 K, emitted by the graded-gap solid solution $InAs_{1-x-y} \cdot Sb_x P_y$ ($dE_g/dx = 1.6$ meV/μm). Solid curve (3) - experimental, dashed curves - calculated for the following parameter values: 1) L = = 6 μm, h = 10^5 cm^{-1}; 2) L = 6 μm, h = $5 \cdot 10^3$ cm^{-1}; 4) L = 6 μm, h = = 10^2 cm^{-1}; 5) L = 8 μm, h = 10^3 cm^{-1}.

spectra were recorded for graded-gap semiconductors in the form of the solid solutions $InAs_{1-x-y}Sb_xP_y$ ($0{,}05<x<0{,}12$, $0<y<0{,}16$) at 80 K, using a scanning electron microscope equipped with a special attachment for recording the cathodoluminescence. The figure shows a comparison between the calculated and measured spectra. As can be seem, the curve computed for L = 6 m and S/D = $5 \cdot 10^3$ cm^{-1} provides the best approximation to the experimental results.

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