External x-ray photoelectric effect in negative-electron-affinity cathodes

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The absolute values of the quantum yields in terms of the current for the external photoelectric effect in the x-ray region 0.05–0.25 nm have been found for the first time for negative-electron-affinity cathodes based on III–V compounds for various glancing angles of the radiation. The average emission depth and the emission probability for electrons are calculated from the experimental data.

This letter reports the preliminary results of an effort toward a comprehensive study of the properties of x-ray photocathodes with a negative electron affinity and the development of new types of x-ray detectors and other devices from these cathodes.

There is extensive scientific and practical motivation for research on the x-ray photoelectric effect in negative-electron-affinity emitters. Negative-electron-affinity photocathodes should find applications in x-ray and x-ray-photoelectron spectroscopy, in microscopy and microanalysis, in x-ray diffraction, in radiation physics, in research on solid-state electronics, and in research on the space-time diagnostics of hot laser plasmas and other sources of *x* radiation. Particularly noteworthy is the importance of developing an x-ray photomultiplier which operates without an optical conversion and which has a unique 100% efficiency over a broad spectral region, as well as other hybrid devices, e.g., image converters, with special characteristics.[1–3]

In this letter we are making the first report of measurements of the spectral characteristics (over the wavelength interval 0.5–2.5 Å) and angular characteristics (in the glancing-angle interval 6°–90°) of the quantum yield of the x-ray photoelectric effect of negative-electron-affinity emitters. We have studied the temporal stability of the emission and its uniformity along the surfaces of the samples. The samples were negative-electron-affinity emitters based on polycrystalline layers of III–V compounds and their solid solutions, used as dynodes in photomultipliers, and also negative-electron-affinity emitters based on epitaxial GaP_xAs_{1-x} films grown by gas-phase epitaxy on single-crystal GaAs substrates. The experimental apparatus included a radiation source, a monochromator, a photon counter of known efficiency, and a sealed-off glass container holding the negative-electron-affinity emitters. The glass container held eight samples at a time. The samples were moved and rotated by means of a magnet. The surfaces of the photocathodes were activated to a state of a negative electron affinity by means of cesium and oxygen. The photoemission was measured with an electrometer operated in the current mode. The quantum yield in terms of the current was found from the ratio $\kappa_c = i/eN$ electron-photon, where i is the measured photocurrent, e is the charge of an electron, and N is the number of photons per unit time.

A theoretical analysis of the results was carried out on the basis of the ideas developed in Refs. 4–6. In the simplest version of the model, which ignores the reflection and refraction of the x-ray beam, and which assumes that thermalized electrons appear at the point at which the x ray is absorbed, the ratio κ_c is given by

$$\kappa_c = A\frac{h\nu}{\mathscr{E}}\left(1+\frac{\sin\varphi}{L\mu}\right)^{-1}, \tag{1}$$

where $h\nu$ is the photon energy, $\mathscr{E}$ is the average energy which is expended on the production of a single pair of charge carriers in the conduction band, μ is the linear x-ray absorption coefficient of the medium, $1/L$ is the linear absorption coefficient for the flux of thermalized electrons, A is the probability for the emission of electrons from the surface into vacuum, and φ is the glancing angle of the x-ray beam. Figure 1 shows the spectrum $\kappa_c(\lambda)$ for a single-crystal $GaP_{0.4}As_{0.6}$ sample. In these calculations we took values of μ from Ref. 7, and we used the values $\mathscr{E} = 5$ eV, $L = 4$ μm, and $A = 0.17$. We found the value of the parameter L by comparing the experimental values of κ_{c1} and κ_{c2} measured at the wavelengths $\lambda_1 = 1.54$ Å and $\lambda_2 = 2.5$ Å:

$$L = \frac{\sin\varphi}{k_1 - k_2}\left(\frac{k_2}{\mu_1} - \frac{k_1}{\mu_2}\right), \tag{2}$$

where $k_1 = \kappa_{c2}/\kappa_{c1}$ and $k_2 = \lambda_1/\lambda_2$. The coefficient A was calculated from (1) using the known absolute values of κ_c and the given values of the other parameters.

Figure 1 demonstrates the good agreement between theory and experiment. Figure 2 shows angular curves $\kappa_c(\varphi)$. It follows from (1) that $\kappa_c(\varphi)$ is determined by the relationship between the average x-ray penetration depth $1/\mu$ and the average electron emission depth L. Since these depths are comparable in the case of V $K\alpha$ radiation ($1/\mu = 6.7$ μm, $L = 4$ μm), κ_c is only a weak function of φ. In the case of Cu $K\alpha$ radiation, we would have $1/\mu = 28$ μm; this figure is substantially greater than L, and the dependence approaches a cosecant curve. The values found here for the quantum yield for the $GaP_{0.4}As_{0.6}$ sample are record high values. They are two orders of magnitude above the values of κ_c of the most efficient of the known photocathodes, e.g., CsI. It would appear possible to increase the quantum yield by yet another factor of several

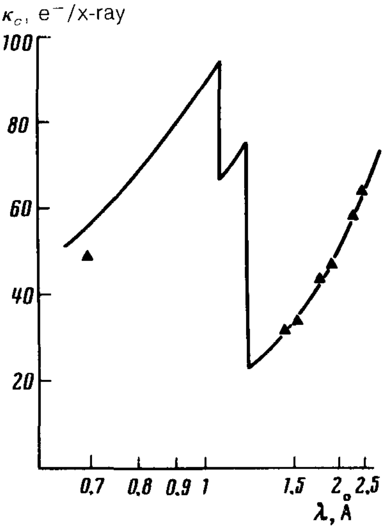

FIG. 1. Spectrum of the quantum yield κ_c for a single-crystal $GaP_{0.4}As_{0.6}$ photocathode at a glancing angle $\varphi = 90°$. Solid line–theoretical; triangles–experimental.

units through increases in the values of the parameters A and L as the surface state is improved and as higher-quality materials are used.

The temporal stability and surface uniformity were studied with the help of two lots of samples, each containing eight samples. In the first lot, all the samples had values of κ_c slightly lower than those in the second lot, and they retained their properties for a year. In the second lot, seven of the samples retain their properties after five months; in only one of the samples do we see a decrease of 20% in the quantum yield.

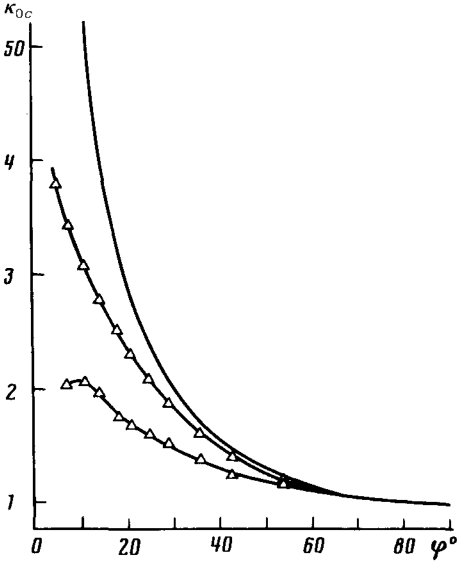

FIG. 2. The angular dependence $\kappa_{0c} = \kappa_c(\varphi)/\kappa_c(90°)$ for a single-crystal $GaP_{0.4}As_{0.6}$ photocathode. 1—Cu $K\alpha$ radiation ($\lambda = 1.54$ Å); 2—V $K\alpha$ radiation ($\lambda = 2.5$ Å); 3—$\kappa_{0c} = \operatorname{cosec} \varphi$.

In the polycrystalline photocathodes, the quantum yield is always lower than that of the single-crystal samples. When we scanned the beam along the surfaces of samples, we observed an angular dependence of κ_c associated with the shape of the dynodes. In the single-crystal samples, this nonuniformity did not exceed 5–10%.

We calculated the spectrum of the quantum yield in terms of the momentum κ_e (the number of emission events per incident photon) for a $\mathrm{GaP_{0.4}As_{0.6}}$ photocathode from the formula

$$\kappa_e = \sum_{n=1}^{n_0} (-1)^{n+1} A^n C^n_{n_0} \left(1 + \frac{n \sin \varphi}{\mu L}\right)^{-1}; \qquad n_0 = \frac{h\nu}{\mathcal{E}}, \tag{3}$$

using the parameter values $A = 0.2$–0.3 and $L = 0.3$–$5\ \mu\mathrm{m}$. The results show that this material has a κ_e value close to 1 over a wide range of the enegy of the incident x rays, from 20 to 0.2 keV. Consequently, the development of an x-ray photomultiplier with a unique spectral characteristic is a realistic project.

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