

sharp boundary of the distribution makes it possible to set the energy scale reliably.

If capture took place in an energy interval that was narrow compared with the width of the electron distribution, the shape of the ion peak duplicates the shape of the distribution, and the shift of the maximum ion current relative to the maximum distribution determines the capture energy. Figures 1 and 2 show the electron distributions in the ion-current curves for SF₆ and CCl₄ (the ion and electron currents are given in arbitrary units, and a common scale is used). The correspondence in the shapes of the ion peaks and of the electron distribution in the region of the maxima is evidence that resonant electron capture in a narrow energy interval takes place for SF₆ and CCl₄. From the shifts of the maxima it was determined that the capture takes place at 0 ± 0.01 eV in SF₆ and 0.02 ± 0.01 eV in CCl₄ (in both cases the values are obtained by averaging eight measurements).

The resonant capture cross-section of SF₆ and CCl₄ was found under the assumption that the capture takes place in an energy interval of 0.05 eV. The cross-section was determined from the maximum ion current and from the electron current in the interval from 0 to 0.05 eV, and calculated from the formula

$$\sigma = (I_{\max} / \eta \xi) / (\Delta I_{el} / \beta) 3,55 \cdot 10^{16} \cdot 273 (p/T) \lambda L.$$

Here I_{\max} is the maximum ion current, ΔI_{el} is the current of the electrons with energies from 0 to 0.05 eV, p the pressure of the investigated gas, T the temperature of the working region, equal to room temperature, L the length of the working region, η the correction for recapture of ions by the grids that screen the ion collector, ξ the correction for the ion escape, β the correction for the recapture of electrons by the grid that screens the collector, and λ the correction for the elongation of the electron path in the magnetic field.

It was determined as a result that $\sigma = (1.2 \pm 0.4) \times 10^{-15}$ cm² for SF₆ and $\sigma = (1.7 \pm 0.4) \times 10^{-16}$ cm² for CCl₄ (both values were obtained by averaging six measurements).

I thank V. L. Tal'roze for continuous interest in the work and for valuable advice.

¹W. M. Hickam and R. E. Fox, *J. Chem. Phys.* **25**, 642 (1956).

²Marriott, Thorburn, and Craggs, *Proc. Phys. Soc.* **B67**, 437 (1954).

³J. Marriott and J. D. Craggs, *Electr. Res. Assoc. Report L/T*, 308 (1954).

⁴Reese, Dibeler, and Mohler, *J. Research Natl. Bur. Standards* **57**, 367 (1956).

⁵W. W. Lozier, *Phys. Rev.* **46**, 268 (1934).

⁶Fox, Hickam, Grove, and Kjeldaas, *Rev. Sci. Instr.* **26**, 1101 (1955).

Translated by J. G. Adashko

97

QUANTUM YIELD OF INTERNAL PHOTO-EFFECT IN GERMANIUM

V. S. VAVILOV and K. I. BRITSYN

Moscow State University

Submitted to JETP editor November 21, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **34**, 521-523 (February, 1958)

IT is known that at photon energies near the threshold of the internal photoeffect, corresponding to approximately 0.7 eV for pure germanium, the quantum yield is constant and equal to unity.^{1,2} This is in agreement with the usual concept of the creation of one electron-hole pair upon absorption of a photon.

If the photon has a sufficient excess energy above threshold, additional electrons can be liberated in the crystal as a result of impact ionization. The possibility of a quantum yield of photoluminescence in excess of unity, upon excitation by quanta with energies more than double the energy of the luminescence quantum, was indicated by S. I. Vavilov³ in 1947. This phenomenon was observed experimentally by Butaeva and Fabrikant⁴ in short-wave excitation of luminophors and by Koc in an investigation of the internal photoeffect in germanium. Experimental data on the increase in quantum yield by impact ionization with photoelectrons or holes are important from the point of view of the theory of scattering of carriers in a crystal and the theory of impact ionization, developed by Chuenkov⁶ and others.

We measured the quantum yield of the internal photoeffect in N-type germanium in the wavelength range from 1.5 to 0.254 μ . The quantum yield Q was determined as the ratio of the number of excess free carriers to the number of absorbed photons. Single germanium crystals with a specific resistivity ρ ranging from 10 to 20 ohm-cm and with initial diffusion length L of approximately 1.5 mm were used in the experiments. Crystals in the shape of platelets 0.3–0.6 mm thick and approximately 1 cm² in area were illuminated on one side by

monochromatic light. On the opposite side, indium was fused into the platelets² to produce an N-P junction. Light of the required wavelength was separated by a monochromator with a quartz prism. The light sources were a SVDSH lamp for the infrared and visible regions, and a PRK-4 mercury quartz lamp for the ultraviolet region. The energy flux of the incident beam was measured with a compensated thermopile calibrated against a Hefner lamp.

The receiver for the 366, 313, 289, and 254 μ lines in the ultraviolet region comprised the luminescent compound "lumogen," which has a constant glow yield, and a FEU-25 photomultiplier. Calibration was by direct comparison with the readings of the thermopile at a wavelength of 365 μ .

The quantum yield was calculated from the formula

$$Q = Ihc/\alpha e \lambda P_i (1 - R), \quad (1)$$

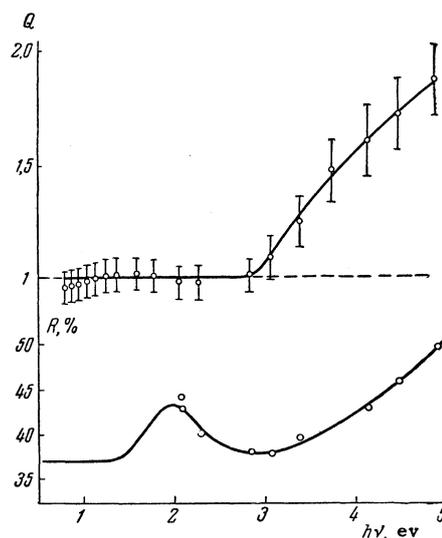
where A is the short-circuit current between the N and P regions, corresponding to a hole current from the N region, where the photons are absorbed, into the P region of the crystal; P_i is the power of the incident radiation; α is the coefficient of carrier collection, which in this case can be calculated from

$$2/\alpha = (1 + SL/D) e^{d/L} + (1 - SL/D) e^{-d/L}. \quad (2)$$

Here L is the diffusion length of the excess carriers in the N-region, d the thickness of the crystal, D the bipolar diffusion constant, and S the speed of the surface recombination.

The total coefficient of reflection R , as was already indicated,⁷ depends on the method of treating the germanium surface, which is etched to reduce the speed of surface recombination. R was measured with an integrating photometric sphere that permitted determination of the ratio of the coefficient of reflection from the investigated germanium crystals to that from the surface of a thick layer of magnesium oxide, whose coefficient of reflection is known. The radiation receiver used in the ultraviolet region, as in the measurement of the energy flux, was a layer of "lumogen" and a photomultiplier.

The diagram shows the curve $R(h\nu)$ and the values of the quantum yield in the energy range of photons from 0.83 to 4.9 eV, calculated from formula (1). The quantum yield vs. photon energy curve shows clearly the considerable increase in Q , which, however, begins not with the energy of the liberated electron (≈ 1.4 eV), but at higher energies. This was to be expected on the basis of the work by Chuenkov,⁶ according to which the probability of impact ionization is negligibly small



compared with the probability of energy transfer at carrier energies only slightly above the width of the forbidden band. According to Chuenkov's calculations, the probability of impact ionization reaches a value of $\frac{1}{2}$ at a carrier energy of approximately 2 eV. At large values of $h\nu$ the rise in the quantum yield slows down, i.e., the mean energy ϵ , expended on the production of the electron-hole pair, increases. It was observed in experimental investigations of the "multiplication" of fast electrons in germanium, that increasing the electron energy W leads also to a certain increase in ϵ , whose value is 3.7 ± 0.4 eV at $W = 5 - 15$ keV and to 4.5 - 5 eV at $W = 500 - 1,000$ keV.⁸

The authors express deep gratitude to M. N. Alentsev, B. M. Vul, and V. A. Chuenkov for criticism and advice.

¹ P. S. Goucher, Phys. Rev. **78**, 816 (1950).

² V. S. Vavilov and L. S. Smirnov, Радиотехника и электроника (Radio Engineering and Electronics) **1**, 8, 1147 (1956).

³ S. I. Vavilov, "Luminescence and its Duration," 1947. Collected Works, Vol. 2, Acad. of Sciences Press, 1952, p. 293.

⁴ F. A. Butaeva and V. A. Fabrikant, Izv. Akad. Nauk SSSR, ser. fiz. **21**, 541 (1957); **18**, 2 (1954).

⁵ S. Кос, Ceskoslov. Casopis pro fisiku **6**, 668 (1956).

⁶ V. A. Chuenko, Izv. Akad. Nauk SSSR, ser. fiz. **20**, 1550 (1956).

⁷ Vavilov, Gippius, and Gorshkov, J. Tech. Phys. (U.S.S.R.) (1957) (in press).

⁸ Vavilov, Smirnov, and Patskevich, Dokl. Akad. Nauk SSSR **112**, 1020 (1957), Soviet Phys. "Doklady" **2**, 93 (1957).

Translated by J. G. Adashko