

Electroluminescence of Semiconducting Diamonds

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Electroluminescence has been observed in Type IIb diamonds. With both alternating and direct current, the light is emitted in the vicinity of a point contact electrode when this electrode is negative. The spectrum consists of a single broad band centered at 4400 Å. The variation of the electroluminescent intensity with current voltage and frequency is reported. This behavior is typical of carrier-injection electroluminescence.

WE wish to report the observation of electroluminescence in several Type IIb diamonds. These diamonds are *p*-type semiconductors^{1,2} which act as rectifiers when a potential is applied between a large area contact and a point probe. When a potential of 200 or 300 volts was applied between such contacts in the direction of easy current flow (probe negative), a purple-blue light was visible in a normally lighted room at the point where the probe touched the diamond. The same characteristic color was observed with all the probe materials which were used (aluminum, copper, nickel, platinum, tungsten, several thermocouple alloys, and graphite); with ac as well as dc; in air, in several transparent liquids, and in high vacuum. In one diamond the light appeared to come from several points within the crystal as well as the point contact.

More detailed experiments were carried out on one diamond.³ This was a rectangular cut diamond (dimensions about 1×1×8 mm) with a room temperature resistivity of 6000 ohm cm. A graphite block was pressed on to the diamond and a Chromel wire (0.002 in. diameter) was wedged under the diamond. When a potential was applied between these contacts, the light appeared at one or more points along the fine wire. To avoid air discharges which often accompanied the electroluminescence, the diamond was immersed in silicone fluid *MS 200*.

The spectrum of the emitted light was photographed with a quartz prism spectrometer while the diamond was excited with ac (400 volts peak at 100 cps). The spectrum consisted of a single broad band in the blue and violet region. The intensity reached a maximum at a wavelength of about 4400 Å (2.8 eV) and fell to $\frac{1}{10}$ of this maximum value at about 3900 Å and 4850 Å. This spectrum is different from that of the blue fluorescence which has been observed in Type I diamonds.⁴ The phosphorescence which has been observed in other Type IIb diamonds¹ extends much further into the green and has a more complicated structure.

The brightness waves were detected with a photomultiplier and displayed on an oscilloscope. In Fig. 1 the upper trace is the applied voltage (200 volts peak at 100 cps) and the lower trace is the brightness. The single brightness peak in each cycle occurs when the point contact is negative. The peak remained in phase with the applied voltage at all frequencies up to 20 000 cps. The time of buildup or decay of the light output was therefore much less than 50 μ sec.

The current and the light intensity varied with the position of the fine contact on the surface of the diamond and were usually very noisy. Rough measurements of the average intensity were made at various voltages and frequencies. Within the limits of error, the intensity increased linearly with increasing voltage or current beyond an apparent threshold:

$$B = a(V - b), \quad (1)$$

$$B = \alpha(I - \beta), \quad (2)$$

where B is the brightness, V is the applied voltage, and I is the current in the forward direction. The voltage threshold b varied between 50 and 100 volts and β varied between 50 and 100 μ a. With currents up to 300 μ a in the reverse direction, no light was detected. The variation of intensity with frequency at fixed voltage was not reproducible.

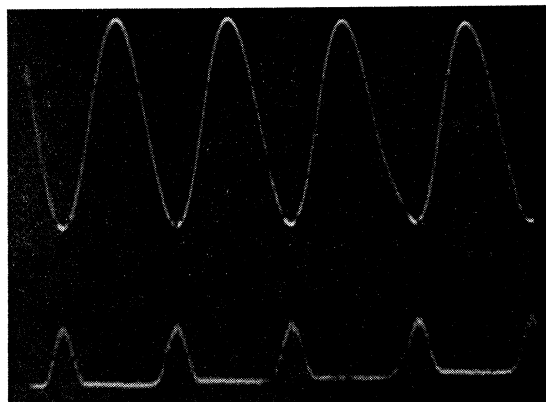


FIG. 1. Applied voltage (200 volts peak at 100 cps) and brightness of electroluminescence. The light is emitted when the point contact is negative.

¹ J. F. H. Custers, *Physica* **18**, 489 (1952); *Nature* **176**, 173 (1955).

² I. G. Austin and R. Wolfe, *Proc. Phys. Soc. (London)* **B69**, 329 (1956).

³ We are grateful to Dr. R. Berman of the Clarendon Laboratory, Oxford, and to Industrial Distributors (1946), Ltd., for lending us this diamond.

⁴ P. G. N. Naylor, *Proc. Indian Acad. Sci.* **13**, 483, 534 (1941); **14**, 1 (1941).

The behavior of these diamonds is typical of carrier-injection electroluminescence.⁵ It is probable that electrons are injected into the conduction band at the point contact, the injection efficiency varying with position and frequency. These electrons then combine with holes in the valence band. The recombination must involve energy levels near the middle of the forbidden gap

⁵ G. Destriau and H. F. Ivey, Proc. Inst. Radio Engrs. 43, 1911 (1955).

because the wavelengths corresponding to direct transitions would be shorter than 2500 Å. The emission from interior points in one diamond probably indicated the presence of internal potential barriers.

It seems possible that the electroluminescence described is another characteristic of Type IIb diamonds in addition to the semiconducting properties, the phosphorescence, and the extra infrared absorption peaks.²

Elastic Scattering of Low-Energy Electrons by Atomic Nitrogen and Atomic Oxygen

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The phase shifts and elastic scattering cross sections of atomic nitrogen and oxygen for low-energy electrons have been calculated with central field potentials. Most emphasis has been placed on the Hartree-Fock potentials. In the low-energy range, the WBKJ approximation gives an indefinitely increasing cross section, whereas the integration of the differential equation yields finite cross sections in the limit of zero energy, for both nitrogen and oxygen. The Hartree potential does not allow for the existence of a bound state (negative ion) in either case. The Thomas-Fermi potential, although not reliable for low atomic numbers, does allow for the existence of a bound state (of approximately zero energy) in the case of oxygen.

I. INTRODUCTION

AN understanding of the various processes occurring in the upper atmosphere involves the scattering of low-energy electrons by atomic nitrogen and atomic oxygen. Experiments are difficult in the low-energy

range because of the recombination of the atoms to form molecules. Two calculations of the low-energy elastic scattering cross section of atomic oxygen reported in the literature differ markedly.¹ They are shown in Fig. 1. The cross section given by Mitra, Ray, and Ghosh seems to increase without limit as the electron energy goes to zero (cross sections are given up to 1000 atomic units) whereas the largest value given by Yamanouchi for the limiting case of zero (incident electron) energy is only about 85 atomic units. One of the purposes of this article is to give some insight regarding the cause of this discrepancy.

It is well known that the method of Faxen and Holtzmark can give satisfactory results for elastic scattering from central field potentials. However, one does not know just how to modify the unperturbed *atomic* potentials in order to take into account exchange and polarization effects resulting from incoming electrons. More experimental information is needed to provide a basis for the selection of one out of several alternate methods of accounting for these perturbations. Maintaining a central field approximation has obvious advantages. Holtzmark² was able to obtain agreement between theory and experiment for argon and krypton by using a Hartree field modified by another simple central field to account for exchange and polarization effects. Experiments with rare gas atoms can be carried out more

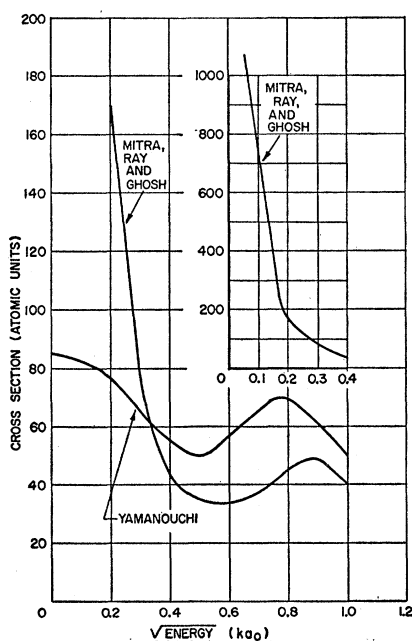


FIG. 1. Previously reported cross section for low-energy electrons and atomic oxygen.

¹ Mitra, Ray, and Ghosh, Nature 145, 1017 (1940); T. Yamanouchi, Progr. Theoret. Phys. Japan 2, 23 (1947).

² J. Holtzmark, Z. Physik 55, 437 (1929); 66, 49 (1930).

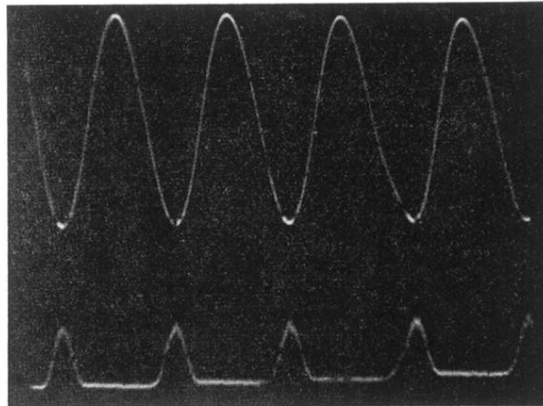


FIG. 1. Applied voltage (200 volts peak at 100 cps) and brightness of electroluminescence. The light is emitted when the point contact is negative.