Letters to the Editor

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Production of Sodium Airglow Excitation by Imprisonment of Resonance Radiation*

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(Received July 6, 1953)

SERIOUS difficulties hamper the understanding of the emission of the sodium D lines in the night airglow on a photochemical basis. In substance the trouble arises from the indications at twilight that sodium in very low concentration is in equilibrium with the atmosphere at least up to 100 km, whereas nocturnal measurements place the airglow layer at 250 km where the concentration of sodium as well as of possible reactants would be far too low to account for the D line intensity observed.[1]

It should be pointed out that a resonance photon, originating somewhere in a sodium layer containing as many atoms as the twilight measurements imply, has a very good chance of being reabsorbed before it leaves the layer. In fact, calculation shows that in a spherical shell of sodium at 300°K, 100 km thick and containing 10^{11} atoms per cm^2 column, a photon radiated into the upward hemisphere of directions at the base of the layer has a total probability of 0.84 of being captured before it escapes through the top of the layer. As a consequence it appears possible, on the basis of calculations so far completed, to account for the observed concentration of excited atoms on the night side of the earth by transport of imprisoned resonance radiation from the sunlit side.

The theory of imprisonment of resonance quanta developed by Holstein[2] adapted to the present problem of sodium photons with Doppler line shape is simplified considerably in principle compared to the problems he treated because only a steady-state distribution fed by a constant source need be sought. The density of excited atoms in the "dark" region of the atmosphere is then

$$n(\mathbf{r})=\int n(\mathbf{r}')G(\mathbf{r},\mathbf{r}')d\mathbf{r}',$$

where $G(\mathbf{r},\mathbf{r}')$ is the probability that a photon emitted at $\mathbf{r}'$ be absorbed at $\mathbf{r}$. Holstein demonstrates how $G(\mathbf{r},\mathbf{r}')$ may be calculated for various types of line shapes.

Here, unfortunately, the region of integration and the boundary conditions are extremely complex, and recourse must be had to special methods of attacking the problem which will be explained in detail elsewhere.

The results obtained so far indicate that transport of excitation into the unilluminated region is very important for a layer of the type described above, or indeed under conditions which would have to be assumed to account for the excitation on any other basis. Unaided by reflections from the surface and from clouds, the imprisoned photons would, however, be attenuated too rapidly for layers reasonably thin—less than 100 km. But reflection is certain to be appreciable. Perhaps 0.4 of the photons striking the surface of the earth or clouds, would, on the average, be reflected. This, plus the gradual shrinking of the volume of the zones toward the antisolar point into which the radiation travels, appears to be capable of giving a rather constant average density of photons on the night side of the earth. Diurnal fluctuations, as well as the seasonal variation with a maximum in the summer, we believe to be mainly the result of the variations in surface reflectivity, particularly significant changes in cloud and snow cover, and partly perhaps the result of changes in the width of the trapping layer because of variable ionization.

Experiments to test these ideas are in progress. It should perhaps also be suggested here that imprisonment might be of great importance in explaining the excitation of resonance lines of atmospheric constituents other than sodium. Certainly it ought to be considered in connection with the deduction of layer heights and twilight concentrations when resonance photons are involved.

* This work was supported in part by the U. S. Air Force Cambridge Research Center.
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Optical Properties of Indium Antimonide

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(Received July 28, 1953)

RECENT investigators have reported rather divergent values for the forbidden energy gap ΔE in the semiconducting compound indium antimonide InSb. Welker[1] has quoted a value of 0.53 ev and Breckenridge, Hosler, and Oshinsky[2] have reported an activation energy for intrinsic conduction of *ca* 0.4 ev. Both of these values were obtained from measurements of the conductivity as a function of temperature T. They contain the assumptions that the effective masses of electrons and holes are unity, that the carrier mobilities vary as $T^{-\frac{3}{2}}$, and that ΔE is independent of temperature over the investigated temperature range.

The analysis of infrared transmission spectra permits an independent determination of an upper limit for ΔE. However, when we turned to infrared transmission to determine ΔE, we encountered a rather anomalous behavior.

The preparation of indium antimonide and the growth of single crystals have been described earlier.[3,4] Our first samples were prepared from commercial grade 99.8 percent antimony and 99.95 percent indium. This polycrystalline material was stoichiometric to within two parts per thousand and its resistivity was about 10^{-4} ohm cm. The transmission spectrum of a 0.010-inch slice is shown by curve A of Fig. 1. It is characterized by a long-wavelength

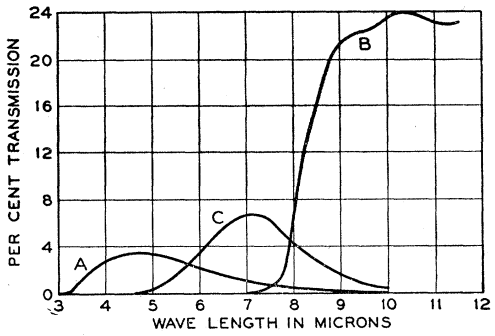

FIG. 1. Infrared transmission of InSb.

limit of absorption near 3.2 microns. This would correspond to an optical gap of 0.39 ev.

In order to increase the resistivity of the compound, it was necessary to refine both the antimony and the compound itself. Zone refining techniques[5] were employed, and material was obtained with a resistivity of about 7×10^{-3} ohm cm. This appears to be the intrinsic resistivity of InSb at room temperature. The transmission spectrum of a typical 0.007-inch slice of a single crystal of this material is shown by curve B in Fig. 1. The long-wavelength limit of absorption now lies at 7.0 microns, corresponding to an optical gap of 0.18 ev. Refining has moved the limit of absorption out 3.8 microns or 0.21 ev.

X-ray diffraction studies have revealed no readily apparent differences in the crystal structure of the two materials characterized by curves A and B. Similarly, annealing below the melting point does not affect the position of the limit of absorption. It would therefore seem that the transmission between 3.2 and 7.0 microns is caused by some impurity which is removed by zone refining. Although this proposal is somewhat unusual, there is other evidence to support it. Material, whose transmission is at first of the type in curve A, can be converted to material similar to B by sufficient zone refining. In addition, by sampling the material between zone refining cycles, the long-wavelength limit of absorption was observed to progress from 3.2 to 7.0 microns. Curve C is the transmission curve of a 0.007-inch slice of such a partially refined sample. Its resistivity was 2.5×10^{-4} ohm cm. Similarly, if a heavily refined bar is examined along its length, it is observed that the limit of absorption moves to shorter wavelengths as one proceeds from the pure to the impure end of the bar. Thus, it appears that the intrinsic limit of absorption lies at 7.0 microns, and the anomalous transmission from 3.2 to 7.0 microns is caused by an impurity with distribution coefficient less than unity.

Selective doping should reveal the nature of the impurity responsible for this behavior, and experiments have been performed in which material with an intrinsic limit of absorption at 7.0 microns is doped with lead, nickel, arsenic, excess indium, and excess antimony. These five agents were chosen since chemical analysis has shown them to be the most abundant impurities in the 3.2-micron material. Doping with up to 0.05 percent lead, arsenic, indium, or antimony produced no observable shift in the long-wavelength limit of absorption. However, an equal amount of nickel caused a shift of about one micron. By adding 0.1 percent of nickel, the long-wavelength limit has been moved to 5 microns. Thus it seems that nickel is at least partially responsible for the anomalous transmission between 3 and 7 microns.

If a single crystal of InSb with a long-wavelength limit of absorption at 7.0 microns at room temperature is cooled to 77°K, the long-wavelength limit shifts to 4.5 microns corresponding to an optical gap of 0.28 ev. Assuming that the change in energy gap is essentially linear over this temperature range, this corresponds to a temperature coefficient for the energy gap of -4×10^{-4} ev/degree K. This coefficient is in excellent agreement with the electrical properties of InSb if the effective mass of the charge carriers is assumed to be 0.083.[4]

We wish to thank R. F. C. Cummings who assisted with the experimental measurements.

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Magnetic Self-Focusing of Auroral Protons

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(Received July 30, 1953)

THE recent beautiful experiments of Meinel[1] on spectra of the aurora show that protons are entering the upper atmosphere at the commencement of an auroral display. From the Doppler spreading to the violet which he observed in H_α, Meinel concluded that the primary protons enter auroral zones with velocities probably greater than 3×10^9 cm sec^{-1}. These speeds are in accord with the original Birkland-Störmer[2] theory of a charged stream of solar particles bent into auroral zones by the earth's magnetic field. The observations therefore throw doubt on criticisms[3] of the theory which argued that such charged streams could not exist as streams because of spreading due to the electrostatic repulsion of the charges.

It is the purpose here to bring to attention an effect which has not been considered in auroral stream theories, namely, the magnetic self-focusing action of ionized streams which was worked out in some detail in 1934.[4] Calculations of this focusing action show that a stream of protons and electrons ejected from the sun in a wide angle cone will rapidly focus itself into a stream having a diameter of the same order as the diameter of an auroral display. Such a stream will be bent into the auroral zones in agreement with the calculations of Störmer. The amount of focusing into the stream depends on the rate of emission of the particles from the sun and on the density of the ionization (which we assume to be electrostatically neutral) in the region between the sun and the earth. Quantitative estimates appear reasonable and will be published. The bearing of the focusing action on corpuscular theories of magnetic storms is being considered.

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Anisotropic Resistivities of Selenium Crystals at High Frequencies

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(Received June 22, 1953)

THE electrical properties of liquid and hexagonal selenium have been presented in four reports.[1–4] The temperature dependence of the resistivity of the crystals grown in a melt[2] was measured at 200 Mc/sec with the same care as described in that report to avoid contributions of end contact resistance and capacitative shunting of the specimens (Boella or Howe effects). The dark resistivities of representative crystals in a rough vacuum are compared with simultaneous dc values in Fig. 1. The dc curves

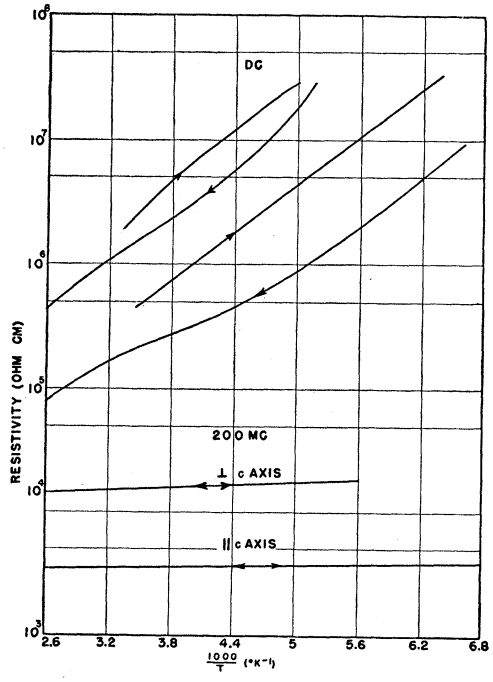

FIG. 1. Anisotropic resistivities of selenium crystals at high temperatures.

behave as previously described.[2] There was, however, no hysteresis in the ac measurements. Data for a number of crystals are presented in Table I. The ratio 3.5 of the average value of $\rho\perp c$