ature curve goes through a point of inflexion at about 1.25°K. This inflexion, however, does not appear to mark any significant anomaly. A similar inflexion was computed and London[6] in their re-evaluation of the vapor pressure data of Abraham *et al.*[5] Moreover, between 1°K and 2.3°K our observed entropy confirms approximately the values[5,6] obtained from the vapor pressure data and from the density data.[7] Below 1° however, the slope of the observed entropy curve does not support the computations either of Abraham *et al.*[5] or of Chen and London.[6]

We have considered in detail the contributions to the entropy of the 4-percent He^4 present (which should show a λ temperature at 0.2°K)[8] and of terms stemming from the possible temperature dependency of the heat of mixing, and have found them to be small. Detailed discussion of these results, as well as of the general procedures involved in the measurements, must be deferred to a later publication.

We wish to express our warm thanks to Dr. C. V. Heer and Dr. V. A. Nanda for their generous help and valuable discussion and to Mr. C. S. Ochs for his welcome help in the measurements.

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Anomalous Optical Absorption Limit in InSb

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TANENBAUM and Briggs[1] have recently encountered an anomalous dependence of the optical absorption limit on impurity content in InSb. They find that the room-temperature absorption limit of an intrinsic sample lies at 7.0 microns while that of a relatively impure sample lies at 3.2 microns. They suggest that the transmission in the region from 3.2 to 7.0 microns is due to an impurity effect. Optical measurements have also been carried out at this laboratory.[2] We find, for example, in agreement with Tanenbaum and Briggs, that the absorption limit of an n-type sample containing 5×10^{18} electrons/cm³ lies at 3.2 microns, while that of an intrinsic sample lies at 7.2 microns. We believe, however, that there is a natural explanation for the anomalous behavior of the absorption limit which is based on the very small effective mass of the electrons in InSb, rather than on some specific impurity effect.

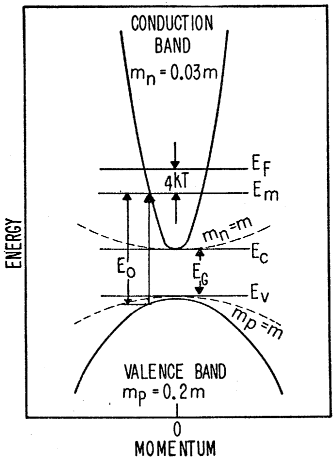

FIG. 1. Energy-momentum diagram of InSb based on $m_n = 0.03m$ and $m_p = 0.2m$ giving the position of the Fermi level and that of the lowest unfilled level in the conduction band for an n-type sample containing 5×10^{18} electrons/cm³. The corresponding energy-momentum curves for a semiconductor for $m_n = m_p = m$ is shown in dotted lines.

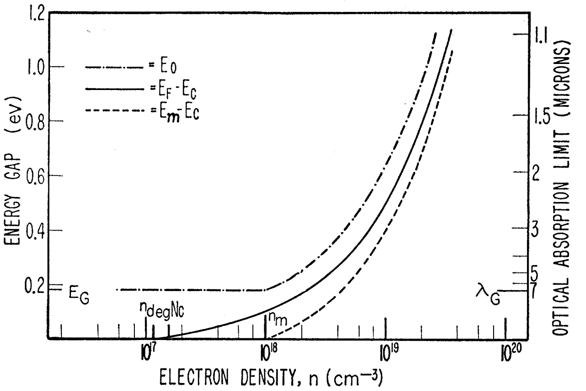

FIG. 2. The dependence of the Fermi level, the lowest unfilled level in the conduction band, and the optical energy gap on charge carrier density in n-type InSb.

By assuming that the thermal-energy gap at room temperature is equal to 0.18 ev, the optical energy gap for intrinsic materials, Tananbaum and Maita[3] obtain a value of $0.083m$ for the geometric mean of the effective masses of the electrons and holes in InSb. In addition, by assuming a $T^{-\frac{3}{2}}$ law for the hole mobilities at high temperatures, they obtain a value of approximately 85 for $(\mu_n/\mu_p)_L$, the ratio of electron to hole mobilities in the lattice scattering range of temperatures. Using the relation $(\mu_n/\mu_p)_L = (m_p/m_n)^{5/2}$ we obtain values of $0.03m$ and $0.2m$ for the effective masses of electrons and holes, respectively, in InSb. The very small effective mass of the electrons in InSb results from a sharp curvature at the bottom of the conduction band and is associated with a small effective density of states and with a small degeneracy concentration ($N_c = 1.6\times10^{17}$/cm³ and $n_{\text{deg}} = 1.2\times10^{17}$/cm³ at 300°K). Consequently, InSb becomes degenerate at relatively low electron densities, and in a degenerate sample the height of the Fermi level above the bottom of the conduction band, $E_f - E_c$, increases very rapidly with increasing electron density.

The optical absorption limit of a degenerate n-type sample involves vertical transitions from the filled band to the lowest unfilled level E_m in the conduction band, which lies approximately $4kT$ below the Fermi level (Fig. 1). The optical energy gap E_0 is therefore given by the energy separation between E_m and the corresponding level in the filled band which, assuming spherical energy surfaces, lies $(m_n/m_p)E_m$ below the top of the filled band, and is not just simply given by the minimum separation between the bands E_G. E_m is located at the bottom of the conduction band, i.e., $E_f - E_c$ is equal to $4kT$ at an electron density of $n_m = 6.5N_c = 1.0\times10^{18}$/cm³.[4] For n-type InSb, E_0 should therefore be equal to E_G when the electron density is smaller than n_m and approximately equal to $E_G + (1 + m_n/m_p)(E_f - E_c - 4kT)$ when the electron density is larger than n_m. For p-type InSb, on the other hand, E_0 should be equal to E_G for hole densities smaller than 1.7×10^{19}/cm³, and approximately equal to $E_G + (1 + m_p/m_n)(E_v - E_f - 4kT)$ for hole densities larger than p_m.

The theoretical dependence of E_0 on charge-carrier density for n-type InSb is given in Fig. 2. For the n-type sample containing 5×10^{18} electrons/cm³, we obtain a theoretical optical energy gap of 0.4 ev which is in agreement with the value of 0.39 ev corresponding to the observed optical absorption limit at 3.2 microns.

InSb appears to be the only semiconductor investigated thus far in which the anomalous behavior of the absorption limit is observed. This may be attributed to the fact that the effective masses of the charge carriers in other semiconductors are much larger than the effective mass of the electrons in InSb, so that a much larger carrier density is needed to make them degenerate.

A shift in the absorption limit with charge-carrier density should also be observable at sufficiently high charge-carrier densities in other semiconductors. However, the absorption by free charge carriers at the high densities needed would, in general, mask the intrinsic absorption limit and thereby prevent the effect from being observed.

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Origin of the Emission of the Oxygen Green Line in the Airglow*

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It is well known that the airglow emission of the oxygen green line at λ5577A cannot be attributed to the ordinary chemical sources if the altitude of the airglow layer is greater than that of the E layer. Furthermore, ionic recombinations involving negative ions in Region F are not sufficient to lead to an airglow emission. Finally, while the hypothesis of incoming particles exciting this emission has been put forward, it remains vague and cannot account for the variations which are observed.

According to the observational data,[1] the height of the emission layer is of the order of 250±50 km, and the maximum of intensity occurs at local midnight ±2.5 hours. The observed annual variation shows several maxima and indicates, therefore, a quite complex variation. Finally, the isophotal plots of the intensity changes of various parts of the sky suggest the presence of a definitive emission pattern in the high atmosphere.

In order to explain such an emission, recourse must be made to results obtained by Nicolet and Mange[2] on the vertical distribution of molecular oxygen. The charge-exchange process considered by Bates and Massey[3] can be applied in the following form in the F_2 layer:

$$O^+ + O_2 \rightarrow O + O_2^+. \tag{1}$$

The reaction (1) is followed by

$$O_2^+ + e \rightarrow O' + O'', \tag{2}$$

namely, a dissociative recombination process first discussed by Bates and Massey[3] and calculated by Bates.[4] Dissociative recombination of O_2^+ is a powerful excitation mechanism for the green line in the airglow.

Because molecular and atomic oxygen are in diffusive equilibrium at 200 km, we can assume the following vertical distributions:

$$n(O) = n_0(O)\exp[-(1+\beta)\zeta], \tag{3}$$

and

$$n(O_2) = n_0(O_2)\exp[-(2+\beta)\zeta], \tag{4}$$

in which $n_0(O)$ and $n_0(O_2)$ denote the concentrations at the reduced[5] height $\zeta = 0$, $n(O)$ and $n(O_2)$ are the concentrations at height ζ, and β is the scale height gradient of atomic oxygen.

Numerical values[2] show that O_2 is still an important constituent in Region F; of the order of 5×10^7 cm^{-3} at 200 km, 5×10^6 at 250 km, 5×10^5 at 300 km and 10^5 at 350 km. According to ionospheric observations,[6] an average peak of the night-time F_2 layer may be considered at heights of the order of 300–350 km. The vertical distribution of the electron concentration n_e can be represented[5] by the following formula:

$$n_e = (n_e)_0 \exp\{\tfrac{1}{2}(1+\beta)[1-\zeta(1-\eta)-e^{-\zeta}]\}, \tag{5}$$

in which η denotes a parameter giving the form of the particular distribution. If $\eta = 0$, the conventional form is obtained in which the total electron content of the layer is three times the content below the peak. If $\eta = 1/(1+\beta)$, the recombination coefficient can be proportional to the pressure and the total electron content is six times the content below the peak. It is known that these extreme forms may represent the behavior of the F_2 layer[7] in winter and summer.

Ionization potentials of O and O_2 being 13.60 ev[8] and 12.04 ev,[9] respectively, O_2^+ obtained by (1) is in the electronic state $(^2\Pi_g)$ from $v=0$ to $v=6$ at most. The dissociation potential of oxygen being 5.11 ev,[10] process (2) *a priori* leads to three possibilities as far as the energy balance is concerned:

$$O_2^+ + e \rightarrow 2O(^1S), \text{ or } O(^1S)+O(^1D), \text{ or } O(^1S)+O(^3P).$$

From this, one concludes that the emission of the green line might be produced by this means. If the complete use of the energy may yield two excited atoms ^1S, it must be pointed out that the rate of the emission processes depends on the repulsion curves of states leading to dissociation products ^1S, ^1D, and ^3P.

At F_2 layer heights, $n(O^+) > n(O_2^+)$, so that, thanks to (3), (4), and (5), we may deduce the following vertical distribution of the green line emission:

$$I_{5577} \propto \exp\left\{(1+\beta)\left[1-\zeta\left(\frac{2\beta+3}{1+\beta}-\eta\right)-e^{-\zeta}\right]\right\}. \tag{6}$$

The gradient of the scale height being $\beta = 0.3$, the peak of the emission corresponds to a value of ζ varying from -1 to -2 below the peak of the electron concentration (300–350 km), i.e., an altitude of 250 km.

It follows from these calculations that an airglow emission in Region F is possible. A complete account of this work will be published elsewhere. This will show the interdependence of the emission of the green line and of the properties of an ionospheric layer in which molecular oxygen ions play an important part on account of vertical transport by diffusion.[11]

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Threshold Energies for Sputtering and the Sound Velocity in Metals

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The author has recently[1] described experiments which show that the minimum threshold energy for sputtering is a function of the angle of incidence of the bombarding ions. Previous attempts to measure threshold energies failed to give reliable results because they were made either in the glow discharge or with wires which are small compared to the ion sheath thickness;[2,3] in both cases, however, the angle of incidence is undetermined.

With a low gas pressure (1 micron) and a large sputtering electrode immersed in a plasma of high density ($10^{11}-10^{12}$ per cm^3), it is possible to avoid collisions of the ions within the ion sheath and to approach the plane case with predominantly