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THE METAL-INSULATOR TRANSITION IN STRESSED GERMANIUM

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Abstract

We study the luminescence from highly excited (111)-stressed germanium above the electron-hole liquid critical temperature. We relate our results to recent screening theories and conclude that a plasma is formed near the excited surface and maintained in steady state. Our results suggest a sharp boundary in space between the plasma and a slightly ionized free exciton gas.

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1. Introduction.

Metal-insulator (M-I) transitions in semiconductors as a function of excitation have been explored experimentally by several people, including Thomas and Rice [1], who report on the formation of biexcitons and trions in unstressed Ge (Ge[4,2]) at a temperature $T \approx 7K$; and Shah et al. [2] who interpret their data in Si as a M-I transition at free electron-hole (e-h) pair densities equal to those derived from Debye-Hückel screening [1],

$$n_{DH}(T) = \frac{k_B T}{E_{BO}} \cdot \frac{1}{11\pi} a_{BO}^{-3} \quad (1)$$

where E_{BO} is the exciton binding energy, a_{BO} is the Bohr radius (both at zero pair density); and k_B is Boltzmann's constant. This type of M-I transition has also received considerable theoretical treatment [3-8], along with the electron-hole liquid (EHL) [3].

In order to gain more experimental information about the metal insulator transition in semiconductors, we have studied luminescence from highly excited germanium under uniform (111)-uniaxial stress. This stress changes the electron-hole configuration to Ge [1,1]. As a result the excited EHL phase diagram in unstressed germanium, with a liquid density of $n_{EHL}(T=0) = 2.3 \times 10^{17} \text{ cm}^{-3}$ and critical temperature of $T_c \approx 6.5K$ [9] is shifted under stress to markedly lower densities and temperatures: $2 \times 10^{16} \text{ cm}^{-3}$ and $3.5K$ [10]. Furthermore, stress changes values of E_{BO} and a_{BO} , yielding M-I transition densities from Eq.(1):

	Ge[4,2]	Ge[1,1]
E_{BO}	4.1 meV	2.65 meV
a_{BO}	112 Å	176 Å
$n_{DH}(4 K)$	1.72×10^{15}	6.86×10^{14}

Stressing Ge lowers n_{DH} by a factor of 3 and allows us to more readily reach the M-I transition density for the same pumping light intensity. Since at $T < T_c$ the EHL luminescence dominates the observed spectrum, to observe the M-I transition, it is crucial to make observations at $T > T_c$. The present experiments can be done immersed in liquid helium rather than gas allowing better temperature control at high excitation levels because $T_c < 4.2 K$.

2. Experimental Results.

A long rectangular high purity Ge sample with dimensions $0.7 \times 0.7 \times 10 \text{ mm}^3$ was stressed in the longitudinal direction parallel to (111). Ordinary tin solder was used as a pad between the stressing rods and the sample because this material is plastic at

room temperature and sufficiently hard at low temperature. The sample was immersed in liquid helium, and the stress was chosen to give the third half integer retardation between the ordinary and extraordinary wave at $\hbar\omega = 700$ meV corresponding to 16 Kg/mm^2 stress. This allowed the very accurate reproduction of the stress from run to run by checking the birefringence. The sample was pumped with a chopped (0.7 msec pulse, 17% duty cycle) 3W CW argon laser focused to a spot less than 0.5 mm in diameter onto the central region of the long sample.

Fig. 1 shows the spectra taken at a coolant temperature of 2.20 K. With an absorbed power of $P_A = 0.07 \text{ W}$ [Fig. 1(a)] the luminescence shows two well resolved components readily attributed to free excitons (FE) at 702 meV, and electron-hole liquid (EHL) at 700 meV. The width of the FE line indicates negligible stress inhomogeneities and a FE temperature very close to that of the coolant. The width of the EHL line is similar to that reported by Feldman et al. [10] and correspond to a density of $2 \times 10^{16} \text{ cm}^{-3}$. With $P_A = 0.27 \text{ W}$ [Fig. 1(b)] where $T \approx 5 \text{ K} > T_C$ (see below) the spectrum can be decomposed into an unshifted FE line and a low energy component to be ascribed below to an electron-hole plasma (EHP), the metallic phase of a M-I transition. At $P_A = 0.81$ [Fig. 1(c)] the two-component character of the spectrum disappears. At this power level we observed a noticeable thermal runaway, i.e., a significant drop of signal during the 0.7 ms excitation pulse. This observation indicates that the FE temperature may be considerably higher than the He temperature for $P_A \geq 0.3 \text{ W}$. At $P_A = 0.27 \text{ W}$ we ascribe the broadening on the high energy side of the FE line to heating effects, and arrive at a FE temperature of $5 \pm 1 \text{ K}$. In Fig. 2 we show the spectra taken with a coolant temperature of 4.2 K. In Fig. 2(a) the EHL luminescence at $P_A = 0.07$ has disappeared ($T > T_C$), leaving only the FE line at 702 meV. At $P_A = 0.27 \text{ W}$ [Fig. 2(b)] the broadening on the high energy side indicates a FE temperature of $7 \pm 1 \text{ K}$ and a pronounced EHP peak at 701 meV is observed. Fig. 2(c) again shows a broad line due to thermal runaway at $P_A = 0.81 \text{ W}$.

We estimate the average total density n (i.e., free carriers, excitons, EHL) due to the exciting light in two independent ways. First, using the absorbed light power $P_A = 0.27 \text{ W}$ ($\hbar\omega = 2.4 \text{ eV}$) with an estimated carrier^A lifetime of 2 μsec , and effective volume of 0.7 mm^3 , and assuming 100% production efficiency we arrive at a density of $n = 2 \times 10^{15} \text{ cm}^{-3}$. The second estimate is obtained by using the phase diagram of Feldman et al. [10] and the observation that EHL is formed at $T = 2.2 \text{ K}$ and $P_A = 0.07 \text{ W}$. In this way we obtain a density $n \geq 1.6 \times 10^{15} \text{ cm}^{-3}$ at $P_A = 0.27 \text{ W}$.

3. Interpretation.

We shall relate our results to the recent calculations of the dynamical screening and band renormalization by Zimmermann et al. [8]. Here the exciton energy was found to be independent of the density n_f of free pairs. This agrees with previous experiments in stress-free Si and Ge [1-2] and with our results on stressed Ge. A down shift with n_f of the band continuum represents the screening of the excitonic binding. From Figs. 1-3 of reference 8 we obtain the following approximate binding energy:

$$E_B = E_{B0} (1 - (2.3 n_f / n_{DH})^{1/2}) \quad (2)$$

In thermal equilibrium the density n_x of excitons is given by

$$n = \begin{cases} n_f^2 \frac{N_x}{N_e N_h} e^{E_B / k_B T} & \text{for } E_B > 0 \\ 0 & \text{for } E_B < 0 \end{cases} \quad (3)$$

Here we have assumed Maxwell-Boltzmann statistics (as in ref. 8), and N_x , N_e and N_h are reciprocal quantum volumes of excitons, electron, and holes, respectively:

$$N = v \left(\frac{m k_B T}{2\pi \hbar^2} \right)^{3/2} \quad (4)$$

where m and v are density of state mass and degeneracy, respectively, of the actual particle. Inserting appropriate parameters for Ge [1,1] we have calculated the maximum total density $n_x + n_f$ of a mixed phase ($n > 0$) as function of temperature as shown in Fig. 3. Also shown is the density $n_{DH}/2.3$ corresponding to the minimum density of an exciton-free plasma. Between these limits the system is bistable [6].

In our experiment we observe two luminescence components for an average pair density of $2 \times 10^{15} \text{ cm}^{-3}$ and $T \approx 5 \text{ K}$. According to Fig. 3 a mixed phase can not exist under such conditions. We conclude that the low energy luminescence component must be due to a plasma which in our geometry is surrounded by a less dense mixed phase. The FE in the latter phase give rise to the high energy component. Since we were unable to investigate the spatial distribution of the luminescence components we can only make a reasonable guess on the transition. As a consequence of the bistability we believe that there is a sharp boundary between the EHP and the mixed phase. Due to the elevated temperature there is no way of establishing equal pressure and chemical potential on the two sides of the boundary as in the case of formation of EHL. On the other hand, there is a con-

siderable flow of particles from the excited region, and this may well establish a steady state in which FE form along a sharp boundary. Preliminary calculations of the properties of the two phases indicate that the plasma is very compressible due to the band renormalization, and that this favors the mixed phase in the transition region. Therefore, the density at the boundary is expected to be close to the high density limit of the bistability domain (see Fig. 3(c)).

Due to the inherent ambiguities in a decomposition of the measured two-component spectra we have only made very crude estimates of the line shapes. We find that the EHP component is asymmetric with a pronounced low energy tail. This shape can be understood qualitatively by assuming a non-uniform plasma: the emission from dense regions is broad and at low energies (large band renormalization) while emission from less dense regions is narrower and at higher energies.

4. Conclusion.

We have based our interpretation of the two-component luminescence above the critical temperature for formation of EHL on the simultaneous presence of a plasma and a slightly ionized FE gas. We suggest that the surface excitation used leads to the formation of a non-uniform EHP near the laser spot. As this plasma expands into the crystal, excitons are formed along a sharp boundary. The density at this boundary is expected to be close to the maximum density of a mixed phase rather than the minimum density of an exciton-free plasma.

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FIGURE CAPTIONS

Figure 1. Luminescence spectra from uniaxially (111) stressed (16 Kgf/mm²) Ge immersed in liquid He with a temperature of 2.2 K. (a) absorbed laser power = 0.07 W, gain = 10, (b) absorbed laser power = 0.27 W, gain = 2.5, (c) absorbed laser power = 0.81 W, gain = 1.

Figure 2. Luminescence spectra from uniaxially (111) stressed (16 Kgf/mm²) Ge immersed in liquid He at 4.2 K. (a) absorbed power = 0.07 W, gain = 10, (b) absorbed power = 0.27 W, gain = 2.5, (c) absorbed power = 0.81 W, gain = 1. The onset of the low energy peak at 701 meV between (a) and (b) is ascribed to the metallic phase of an M-I transition, occurring at a density approximately $\sim 10^{15}$ cm³.

Figure 3. Phase diagram of Ge (1,1). (a) is the gas-liquid coexistence curve from ref. 10, (b) is the density $n_{DH}/2.3$ corresponding to the minimum density of an exciton-free plasma, and (c) is the maximum density of a mixed phase. The parameters are $E_{BO} = 2.65$ meV, $a_{BO} = 176$ Å, $m_e = 0.219 m_o$, $v_e = 2$, $m_h = 0.088 m_o$, $v_h = 2$, $m_x = 0.418 m_o$ and $v_x = 4$.

Fig. 1

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Fig. 2

Fig. 3

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