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THE PARTIAL COMPOSITION OF A DENSE ELECTRON-HOLE SYSTEM AND THE EXCITON-PLASMA TRANSFORMATION IN UNIAXIALLY STRESSED SILICON

V. D. Kulakovskii, I. V. Kukushkin and V. B. Timofeev

Institute of Solid State Physics, Academy of Sciences of the USSR, 142432 Chernogolovka, USSR

Two phase region of the gas-electron-hole liquid in Si stressed elastically along the <100> axis is determined and the critical temperature is estimated equal to T_c=14±1.5K. It has been found that on growth of density up to r_s =2.7±0.3 and at T < 12.5K the gas phase consists predominantly of excitons and excitonic molecules. It has been found that at T>T_c the excitonic state are destroyed at densities corresponding to r_s =2,5÷2.

1. The electron-hole liquid (EHL) stability is very sensitive to the orbital degeneracy of energetic spectrum and decreases when the degeneracy is lifted. In Si(2-1) which corresponds to the crystal highly stressed along <100> direction the binding energy is four times less than that in unstressed silicon [1]. Due to this the gas-EHL coexistence boundary in Si(2-1) moves toward high density side by an order of magnitude. It appears, that at low temperatures in such dense e-h gas exciton and biexciton concentrations are of the same order of magnitude [1,2]. This enabled to study experimentally the partial composition of the gas phase (excitons, excitonic molecules, free carriers) up to densities corresponding to r_s ≈2.5 (dimensionless parameter $r_s=(3/4\ n)^{1/3}a_B^{-1}$, a_B - Bohr radius) with use of the emission spectra and photoconductivity and to analyse the problem of exciton-plasma transition (EP-transition).

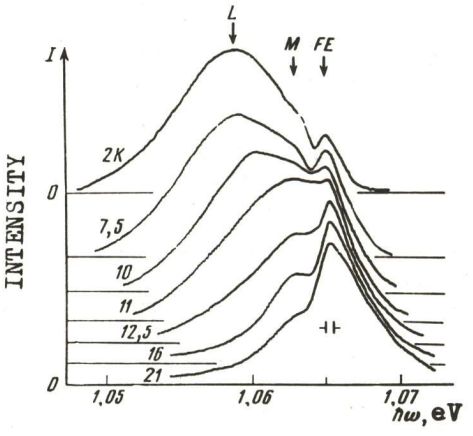

Fig.1 Temperature dependence of emission spectra of Si(2-1) under pulse pumping ($n=1.5\cdot10^{17}$ cm^{-3}). Spectra were measured with 0.15 μsec gate delaying relatively an excitation pulse on 0.05 μ sec.

2. Figure 1 represents spectra of Si(2-1) under pulse laser pumping creating average concentration of e-h pairs $n=1.5\cdot10^{17}$ cm^{-3} measured at different temperatures. Up to T=12.5K there are three lines in spectra - L, FE, M corresponding to EHL, exciton and excitonic molecule emission. The gas densities $n_g(T)$ were defined with the use of onset measurements of L and FE intensity ratios at different n. To determine the absolute values of density n the

calibration measurements under high excitation level corresponding to excitation of the degenerate e-h plasma with $n=5\cdot10^{17}$ cm^{-3} were performed. At low temperatures T< 4K the volume excitation was realized and n was determined with use of absorbtion coefficient, recombination time and density flux data. The EHL density n_o was defined from the EHL lineshape analysis [3]. The equilibrium curves characterized phase boundaries at the liquid - $n_o(T)$ and the gas - $n_g(T)$ sides are represented at Fig. 2. The critical temperature was estimated equal to $T_c=14\pm1.5$K.

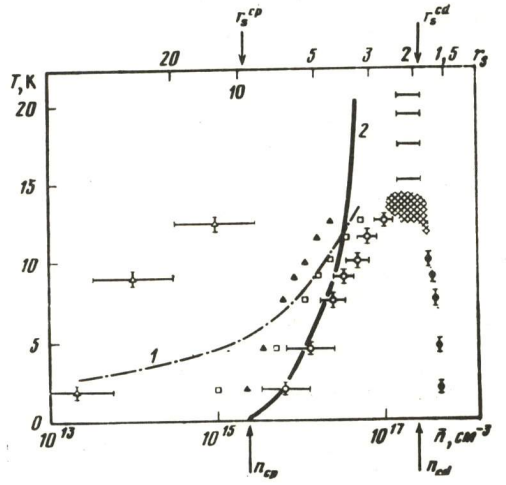

Fig.2 The gas-EHL phase diagram in Si(2-1): • -liquid phase density, o - saturated e-h gas density, □ -exciton density, ▲ - excitonic molecule density, Δ - free carrier density. Curve 1-thermodinamically equilibrium density of exciton gas, curve 2 - the Mott transition line. The gas-EHL critical region is shaded.

3. The absolute values of exciton and biexciton concentrations in the gas phase were determined from the ratio of the integral intensity of the FE and M lines. The recombination probability ratio for molecules and excitons equal to 2,3 calculated on the basis of variational wave function of the excitonic molecule [4] was taken into account. The free carriers concentration was defined from photoconductivity data. The concentrations of excitons, molecules and free carriers found in such way at the gas-EHL phase boundary are represented in Fig.2. It could be seen that up to T=12.5K the gas phase consists mainly of excitons and molecules, although saturated gas density n_g exceeds critical density for EP-transition calculated on the basis of criteria for plasma screening of the Coulomb interaction for excitons ($r_o=0.84\ a_B$ [5]). In contrast to unstressed Si and Ge crystals, the exciton ionization catastrophe in Si(2-1) occurs close to the critical region of the gas-EHL transition. Due to this the transformation of exciton emission spectrum into the structureless spectrum of the plasma was investigated at $T\gtrsim T_c$. Fig. 3 represents kinetic of the emission spectra at T=21 K and pulsed excitation ($n=4\cdot10^{17}$ cm^{-3}). The smoothing of the FE and M discrete spectra observed at small delays ($\sim 0.05\ \mu$sec) and temperatures T=13-20K is associated with the exciton ionization destroying. Note that observed transformation in spectrum has a diffuse character. The magnitude of density when such transformation takes place at T=13-21K is estimated equal to $n=1.5\div3\cdot10^{17}$ cm^{-3} ($r_s^c=2$-2.5). In Fig.2 the arrows indicate the magnitude of the EP-transition critical densities calculated on the basis of the Mott criterion (critical density $r_s^{cp}\approx10$ [5]) and with use of the dielectric screening of the Coulomb interaction (critical density $r_s^{cd}=1.8$ [6]). It could be seen from Fig.2 that experimentally observed density when EP-transition occured is close to the value of r_s^{cd} evaluated within approximation of the dielectric screening of excitons.

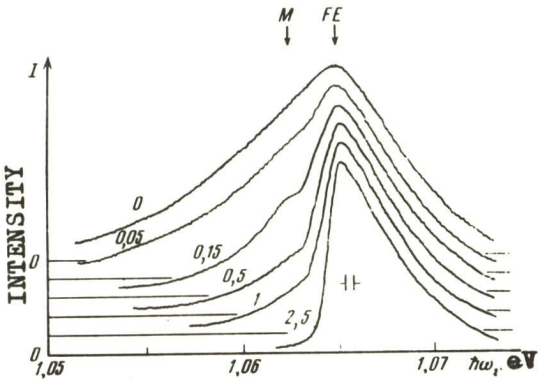

Fig.3 Kinetics of emission spectra of Si(2-1) under pulsed surface pumping ($n \approx 4 \cdot 10^{17}$ cm^{-3}) at T=21K. Figures on spectra indicate the time delays of the gate in μsec. The gate-pulse length is 0.1 μsec.

4. Now let us consider the situation concerning the partial composition of the gas phase at the coexistence boundary with EHL in a compressed Ge. The EHL stability in Ge remains too large ($\varphi \approx 0.28$R, R-excitonic Rydberg) with respect to the excitonic molecule binding energy ($\Delta \approx 0.03$R) even under the condition of the high uniaxial stress along <111> axis when the orbital degeneracies of the bands are completely lifted. Due to this the partial fraction of the EM with respect to FE in the gas phase in Ge <111> at low temperature is too small in order to select the EM radiative decay from the emission spectra. Recently we have shown that the EHL binding energy might be decreased to the value $\varphi \sim 0.18$R in Ge compressed along nonsymmetrical direction close ($\sim 5°$) to the <001> axis [7]. It has been found that in this case the partial fractions of excitons and molecules in the gas phase at the coexistence boundary with EHL at T=2K are of the same order of magnitude. Under such conditions the EM-radiative decay line in the emission spectra (so-called M-line) has been selected), the shape of M-line has been analyzed and EM binding energy has been estimated with value equal to $\Delta \approx (0.15 \pm 0.1)$meV [7]. Due to the differencies between excitonic binding energy scales in germanium and silicon with factor 5 the partial composition of the gas phase at 2K in Ge stressed along the <1, 1, 16> axis approximately coincides with that in Si(2-1) taken at 9K. As well as in Si(2-1) the ionization destroying of the excitonic and excitonic molecule states and transformation into e-h plasma at $T \gtrsim T_c$ in Ge stressed along the direction <1,1,16> occurs at densities close to $r_s = 2.5$ in agreement with criterion of dielectric screening of Coulomb interaction. Such transformation into e-h plasma in germanium like silicon has a gradual character.

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