SPACE-CHARGE LAYERS IN SEMI-INSULATING GaAs: PHOTOEXCITED TWO-DIMENSIONAL ELECTRON SYSTEMS

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Resonant Raman spectra of photoexcited semi-insulating GaAs and Fe/GaAs show features characteristic of two-dimensional electron plasmas. The results are ascribed to the presence of a space-charge layer at the surface, originating in a slight mismatch of Fermi-level positions at the vacuum (or metal) interface and in the bulk. Calculations using values of intersubband transition energies from the data give an estimated shift of ~0.04 eV for the Fermi-level position at T = 85K.

Two-dimensional (2D) electron systems in semiconductor structures have received considerable attention in the past few years.[1,2] In this work,we report on 2D systems resulting from the photoexcitation of semi-insulating (SI) GaAs. Evidence of 2D behavior is provided by measurements of resonant Raman scattering (RRS).

A schematic real-space band diagram of SI-GaAs is shown in Fig. 1. The Fermi-level E_F in the bulk is expected close to midgap values whereas, at the surface, pinning due to the presence of defect states occurs at ~0.6-0.8 eV (T = 300K) from the valence band maximum (VBM).[3] A band bending results due to different E_F positions in the bulk and at the surface. The confining potential can bind either electrons or holes depending on the sign of ΔE_F (the former case is contemplated in the diagram of Fig. 1). The electric subbands at the SI-GaAs surface are in principle empty, but can be populated through photoexcitation. This is analogous to the behavior of undoped quantum-well-heterostructures.[4] Also, the radiative recombination of photogenerated electron-hole pairs should be largely prevented by the spatial separation of carriers induced by the bending, as in n-i-p-i systems.[2] Our experiments show indeed that very modest power densities P ~ 4W/cm^2 result in an appreciable population of the subbands.

The dopant concentrations, the room temperature resistivities (ρ) and carrier densities (n) of the SI-GaAs samples used in the RRS experiments are listed in Table I. They were grown by liquid encapsulation Cczochralski (LEC) as reported elsewhere.[5] All the samples were found to be n-type. Both (100) and (110) surfaces were examined. One of the samples consists of a 50Å Fe-overlayer deposited by molecular beam epitaxy on GaAs (110).[6] As indicated in Table I, 2D behavior was found in samples simultaneously doped with Cr and either Te or Sn donors.

RRS experiments were performed in the region of the $E_0 + \Delta_0$ - gap of GaAs, using the 6471Å Kr^+-line and a DCM dye. The same beam was used to generate the plasma, with P in the range 4×10^0-2×10^4 W/cm^2. Most of the data were taken at T ~ 85K. Spectra recorded at 4K revealed no significant differences.

Data were obtained in the parallel $z(x+y,x+y)\bar{z}$ and crossed $z(x-y,x+y)\bar{z}$ backscattering configurations in the case of (100) surfaces and in the $x+y(x-y,x-y)\overline{x+y}$ and $x+y(x-y,z)\overline{x+y}$ parallel and crossed polarization geometries for (110) faces; z is along [0,0,1] and x+y,x-y denote orthogonal equivalent [1,1,0] directions. The $E_0+\Delta_0$ resonance leads to enhancement of electronic scattering associated with carriers in the conduction band.[7] For both surfaces, the parallel (crossed) geometry allows scattering by charge (spin)-density fluctuations.[7]

At the lowest values of P, the spectra behave in all cases as expected for bulk (undoped) GaAs. Scattering by the transverse-optical (TO) mode is observed from (110) faces in the two geometries, as predicted by symmetry. Due to the resonance, both (100) and (110) surfaces show longitudinal-optical (LO) scattering in the parallel configuration. Except for minor frequency shifts of the Raman lines attributed to laser heating, the spectra of undoped-GaAs and GaAs:Cr do not depend on P. The same applies to TO scattering for all samples.

Intense photoexcitation of GaAs:Cr,Te, GaAs:Cr,Sn and Fe/GaAs:Cr,Te leads to the appearance of new, broad Raman features at ~10-20

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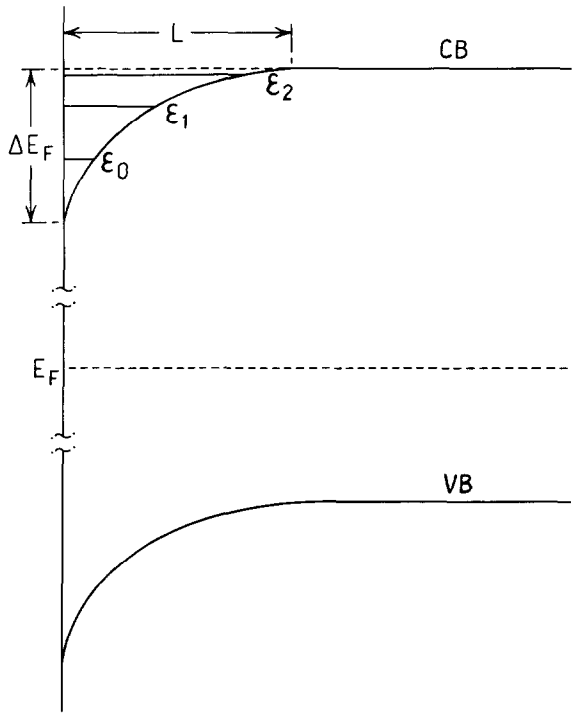

Figure 1: Schematic diagram of conduction (CB), valence band (VB), and conduction subbands at the SI GaAs-vacuum (metal) interface. The length of the space charge layer L and the Fermi-level difference ΔE_F are indicated.

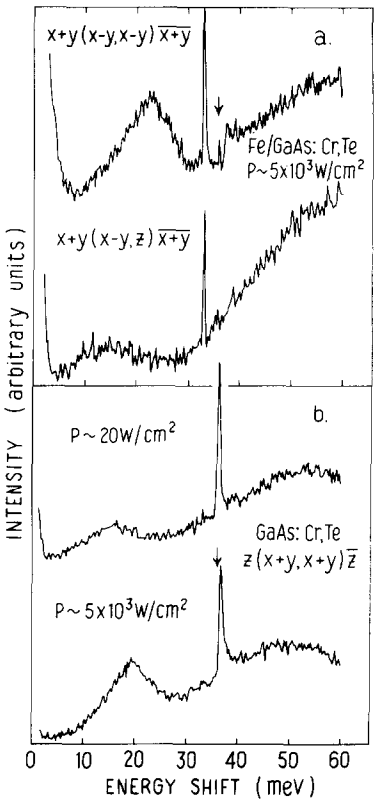

Figure 2: Raman spectra at T ≈ 85K and laser energy ω_L = 1.916 eV (6471Å) for two different samples. The broad structure in the range 10-30 meV corresponds to $\varepsilon_0+\varepsilon_1$ subband transitions. The second trace from the top shows single-particle excitations and the others charge-density-fluctuations. TO scattering is observed in (a) at 34.1 meV. Arrows indicate the expected position of the LO mode of GaAs (36.7 meV). The background above ~30 meV is due to $E_0+\Delta_0$-luminescence.

meV,and luminescence associated with the $E_0+\Delta_0$-gap . As shown in the spectra of Figs.2 and 3, the new Raman bands occur in both configurations, and show a non-linear power dependence. The position of the band in the cross geometry is independent of power density in contrast to the behavior of the parallel configuration which exhibits a shift to higher energies with increasing P (see Fig.2b) This is

Table I: Sample parameters. The Cr(N_{Cr}), Te(N_{Te}) and Sn(N_{Sn}) dopant concentrations; the resistivities (ρ) and carrier densities (n) at T = 300K are indicated. Asterisk (*) denotes samples for which two- dimensional electron scattering was observed.

	Surface	N_{Cr} (cm^{-3})	N_{Te} (cm^{-3})	N_{Sn} (cm^{-3})	ρ (Ωcm)	n (cm^{-3})
GaAs	(100)	--	--	--	4.6×10^{7}	1.4×10^{8}
GaAs:Cr	(100)	4×10^{16}	--	--	1.3×10^{8}	2.0×10^{8}
*GaAs:Cr,Te	(100)	3×10^{16}	1×10^{16}	--	5.1×10^{8}	2.9×10^{7}
*GaAs:Cr,Sn	(110)	6×10^{16}	--	2×10^{16}	1.0×10^{8}	3.0×10^{8}
*50Å-Fe/GaAs:Cr,Te	(110)	2×10^{16}	6×10^{15}	--	1.2×10^{9}	1.1×10^{7}

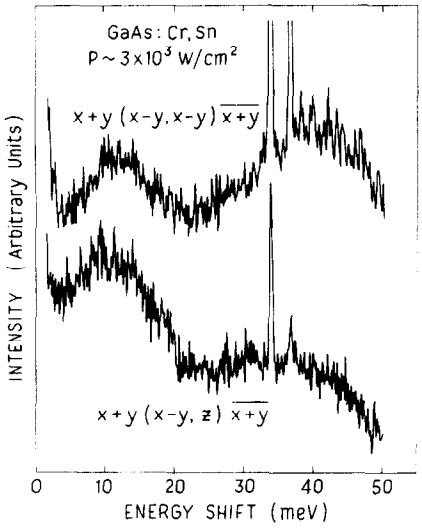

Figure 3: Raman spectra of GaAs:Cr,Sn at ~85 K and ω_L = 1.904 eV, showing intersubband transitions at ~10-15 meV. The narrow lines at 34.1 and 36.7 meV are the TO and LO phonons. $E_0+\Delta_0$- luminescence is observed at ~30-40 meV.

accompanied by a parallel shift and the development of a marked asymmetry of the LO-peak (top and bottom traces in Fig.2).

The features of the scattering discussed above and also the fact that the Raman bands appear only under resonant excitation indicate that they are due to photoexcited electrons.[7] Consequently, the crossed-geometry band is assigned to single-particle excitations (spin-density fluctuations). The parallel configuration corresponds to charge-density fluctuations which are electrostatically coupled to the LO-mode. This coupling is responsible for the shift and asymmetry that develops in the latter at high powers.[7]

A question arises as to the 2D or 3D nature of the carriers involved in the scattering. The 3D case implies identifying the structure in the parallel geometry as due to a plasmon-LO coupled mode at a carrier density $n \sim 2(0.8) \times 10^{17}$ cm^{-3} for samples codoped with Te(Sn). This concentration corresponds to $qV_F \sim 15(10)$ meV (q is the photon wavevector and V_F the Fermi velocity), a value that is inconsistent with the position of the maximum of the single-particle structure at ~15(12)meV. The estimated value of n is also inconsistent with P being as low as 20 W/cm^2. Power densities a factor of ~10^4 larger appear to be required to generate such populations in GaAs.[8,9] These considerations and, moreover, the lack of P-dependence of the single-particle spectra point to the 2D nature of the scattering. Accordingly, the bands are assigned to intersubband ($\varepsilon_0 \rightarrow \varepsilon_1$) transitions of electrons confined at the surface (see Fig.1).

The bare $\varepsilon_0 \rightarrow \varepsilon_1$ transition energy is determined in the crossed scattering geometry.[7] Using the measured values of ~15 and 12 meV, for GaAs:Cr codoped with Te and Sn, we can estimate the band bending (ΔE_F) by numerically solving Schroedinger's equation with the (quadratic) potential determined by the space charge layer of width $L = (\varepsilon_s \Delta E_F / 2\pi e^2 N_{SC})^{1/2}$, where ε_s is the static dielectric constant of GaAs and N_{SC} is the space charge density (see Fig. 1). The potential due to the photogenerated charges can be neglected for densities $<<N_{SC}L$. For $N_{SC} = 3\times10^{16}$cm^{-3}, we obtain ΔE_F = 0.045(0.038) eV and L = 460(420)Å for Te(Sn)-codoped samples. The actual values of N_{SC} are expected somewhere in the range 2×10^{16} - 4×10^{16} cm^{-3} (see Table I). For a given ΔE_F, the calculated intersubband energy varies less than ~2 meV within that range.

The dominant impurity in codoped-GaAs (and also GaAs:Cr) is most likely the deep Cr-related acceptor. Accordingly, the bulk location of E_F at low temperatures should be determined by the threshold for $Cr^{3+} \rightarrow Cr^{2+}$ transitions, i.e., ~0.76 eV above VBM (T = 77K).[10] This value, together with $\Delta E_F \sim 0.04$ eV, lead to an estimate of 0.80 eV (from VBM) for the surface pinning position of E_F. The corresponding room temperature value for n-GaAs is 0.75(±0.1) eV, as determined from photoemission data.[3]

We finally refer to the absence of 2D scattering in undoped-GaAs and GaAs:Cr; a fact that we ascribe to a band bending at the surface that is unable to bind electron states. Our calculations set an upper limit: $N_{SC}/(\Delta E_F)^2 \sim 4 \times 10^{22}$ cm^{-3}/eV^2, above which no quasi-2D electron state exists in the well. Clearly, the absence of scattering points to a different value of ΔE_F since N_{SC} is unlikely to be outside the range 10^{16} - 10^{17} cm^{-3}. The actual bending in these samples can of course lead to hole, rather than electron confinement. Scattering by hole states is not accessible to our RRS experiments at the $E_0 + \Delta_0$ - resonance.[7]

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