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Phonon emission from the first and second subbands of a two-dimensional electron gas in silicon detected by exciton luminescence

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The frequency distribution of the phonons emitted by a heated two-dimensional electron gas in a Si metal oxide semiconductor field-effect transistor has been investigated at power densities at which there is significant thermal population of an excited subband. The investigation has been carried out using an exciton cloud detector which uses the fact that phonons of frequency >920 GHz induce a decrease in the bound-exciton (BE) luminescence from the cloud and a corresponding increase in the free-exciton (FE) luminescence as a result of BE$\rightarrow$ FE dissociation. At constant power, the frequency distribution is found to shift to lower frequencies with increasing sheet density rather than to higher frequencies as would be expected for emission from a single subband. This can be qualitatively explained by the increase in the emission of low-frequency phonons from low-wave-number electrons in the excited subband.

INTRODUCTION

The study of phonon emission by a two-dimensional electron gas (2DEG) provides detailed information on the nature of the electron-phonon interaction. In previous work the emission has been detected either by superconducting tunnel junctions[1] or by semiconducting bolometers[2] and in the present paper we report the use of an exciton cloud detector for studying 2DEG's. This type of detector is only sensitive to phonons whose frequency is greater than 920 GHz (Ref. 3) so that it can be used to obtain spectroscopic information on the emission as can a superconducting tunnel junction. Since the exciton cloud can readily be moved, it could also be used to investigate changes in a spectrum with an emission angle and should in principle be usable in magnetic fields unlike the superconducting detector.

The technique has been used here to explore the phonon emission from a 2DEG in a silicon metal oxide semiconductor field-effect transitor (MOSFET). For the samples used, it is known from previous phonon experiments at low powers that the Fermi level, E_F, enters the first excited subband at energy, E_{ex}, when the sheet density $n_s=4.9\times10^{16}$ m^{-2}.[4] Thermal occupation of this subband can occur at lower values of n_s and this has recently been demonstrated in these samples by measuring the 2DEG resistivity as a function of power density P.[5] The resistivity initially rises with P reflecting the increase in scattering with electron temperature T_e. But it then reaches a maximum at P_m and falls and this is attributed to significant occupation of an excited subband of higher mobility that occurs when k_BT_e becomes comparable to $E_{ex}-E_F$.

The present experiments were carried out at values of $P>P_m$ so that phonons should be emitted as a result of intrasubband transitions within both the ground and excited subbands as well as by intersubband transitions. Theoretical treatments are usually restricted to intrasubband transitions from a single subband.[6,7]

EXPERIMENTAL ARRANGEMENT

The experimental arrangement is shown in Fig. 1. The p-type ($N_A=1\times10^{13}$ cm^{-3}) Si samples, which had dimensions $20\times5\times0.4$ mm^3, were from the same batch as those used in previous experiments[4,5,8,9] and contained a (001) MOSFET of 3×1-mm^2 gated area at the center of one of the two 20×5-mm^2 faces. The maximum 2DEG mobility was ~1 m^{2}V^{-1}s^{-1}. The samples were immersed in helium at 2 K and the 2DEG, formed by a positive gate voltage, was heated by 100-ns current pulses using a 20-kHz repetition rate. At the power densities used of 10–100 mW mm^{-2}, the source-drain voltages V_{sd} were

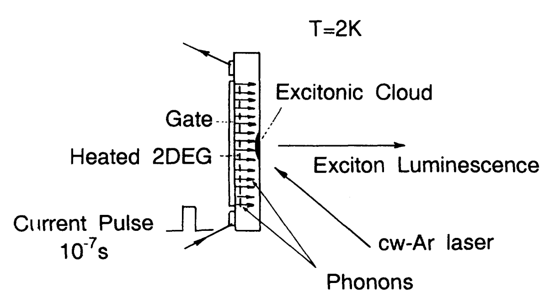

FIG. 1. Experimental setup.

always less than 15 V and as this is small compared with the gate voltages used of 100–200 V [these are large because of the thick (800 nm) oxide layer in the MOSFET] it had little effect on the value or homogeneity of n_s.

To minimize surface recombination of excitons the face of the substrate opposite the device (Fig. 1) was chemically etched to reduce surface damage. During the experiments it was illuminated by a cw argon laser of wavelength 514 nm focused to a spot usually of diameter 0.3 mm to form an exciton cloud at the surface. At 10 K the excitons are essentially all free (FE) but at lower temperatures some of them become bound to impurities (BE). In pure Si exciton annihilation results in a luminescence spectrum with LO and TO phonon-assisted transitions at 1.099 and 1.097 eV, respectively, for FE and a TO phonon-assisted transition at 1.093 eV for BE.[10] However, in the present samples at 2 K, in the absence of an incident beam of phonons, only the BE luminescence line was observed, which is attributable to the relatively high concentration of impurities present in these p-type samples. Phonons incident on the cloud following a 100-ns pulse in the 2DEG create a pulse of FE luminescence $I^F(t)$ together with a decrease in BE luminescence—a negative-going pulse $I^B(t)$. An example of $I^B(t)$ is shown in Fig. 2. The short path length and long pulse length lead to poor mode resolution but we note that the sharp leading edge occurs at about the transit time for ballistic propagation of TA phonons ($t \sim 70$ ns) and that evidence for ballistic propagation of phonons of frequency >920 GHz over distances >1 mm has already been demonstrated.[11]

These effects are qualitatively similar to those seen in experiments using conventional heaters[3] and their interpretation seems clear. The binding energy of an exciton at an impurity is known to be 3.8 meV so the exciton energy levels are as shown in Fig. 3. Phonons of energy greater than 3.8 meV, corresponding to frequencies >920 GHz, can dissociate bound excitons from their impurities resulting in the increase of FE luminescence and decrease in BE luminescence seen experimentally. Indeed, the sizes of the luminescence pulses should provide a direct measure of the intensity of phonons of frequency >920 GHz so may be used to obtain spectroscopic information on the emission from the 2DEG. The size of the pulse was determined by integrating over a 500-ns period. As this is long compared with the ballistic transit time it should include the effect of high-frequency phonons (>1600 GHz) delayed by diffuse scattering by isotopes[12] while phonons of frequency <920 GHz should have negligible effect in

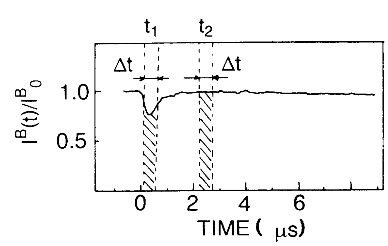

FIG. 2. Bound exciton luminescence pulse induced by phonons from the heated 2DEG. $P=20$ mW mm^2, $n_s=4\times10^{16}$ m^{-2}.

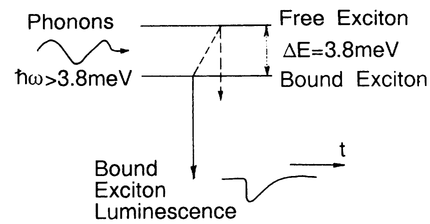

FIG. 3. Energy levels of excitons in silicon.

these samples. This contrasts with the situation in pure Si where they decrease the FE luminescence because the "phonon wind" pushes the free excitons towards the surface of the Si where recombination is more efficient.[3] Evidently this effect should be negligible here because of the very small equilibrium concentration of FE excitons and small exciton lifetime.[3]

RESULTS AND DISCUSSION

Figure 4 shows the relative decrease, S, of the BE luminescence intensity as a function of sheet density n_s for two values of input power density $P=20$ and 60 mW mm^{-2}: In each plot P was kept constant while n_s was changed. S is defined by

$$S = 1 - \frac{\int_{t_1}^{t_1+\Delta t} I^B(t)dt}{\int_{t_2}^{t_2+\Delta t} I^B(t)dt} .$$

$\Delta t = 500$ ns and t_1 and t_2 are chosen so that $I^B(t)$ is measured both with and without phonons incident on the cloud as shown in Fig. 2.

S is taken to be a measure of the phonon intensity of frequency >920 GHz and since P is kept constant, while

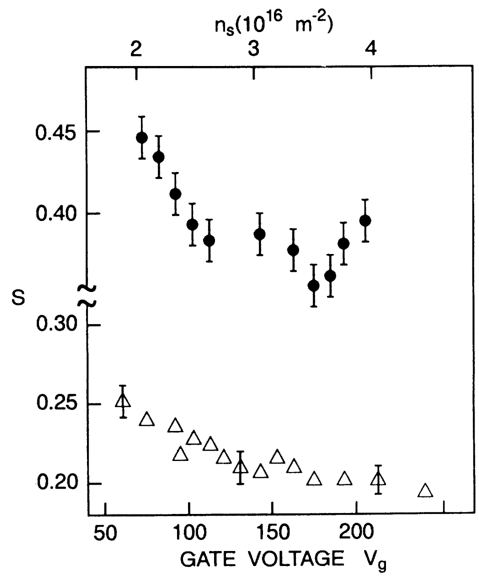

FIG. 4. The relative decrease in BE luminescence, S, produced by a phonon pulse as a function of n_s for two values of injected power density. $P=20$ mW mm^{-2}; $P=60$ mW mm^{-2}.

n_s is varied, changes in S are attributed to changes in the frequency distribution (changes in angular distribution should produce little effect since the area of the emitter is substantially larger than that of the detector). We conclude that the decrease in S seen in Fig. 4 demonstrates a shift in the total phonon emission spectrum towards lower frequencies as n_s is increased.

It is of interest first to compare this result with theoretical predictions for a single subband. For this case the phonon power density emitted for an electron temperature $T_e \gg T$ can be obtained from

$$P(\Omega,s)=\frac{g\Xi_u^2 m^*}{8\pi^4\rho\hbar}\chi_s(\theta)\int_0^{q_D} dq\, q^4 n_{qs}(T_e) \times |F(q_z)|^2\frac{G(q,\theta)}{q_\parallel \epsilon_{sc}^2}$$

where ρ is the Si density, $g=2$, the valley degeneracy for an (001) 2DEG, m^* the in-plane effective mass, Ξ_u a deformation potential, $\chi_s(\theta)$ the angular-dependent polarization factor for modes $s=$LA and TA, $n_{qs}(T_e)$ the occupation number for phonons of wave number q, $F(q_z)$ the boundstate form factor, $G(q,\theta)/q_\parallel$ an emission factor determined by in-plane momentum conservation, $q_\parallel$ is the in-plane component of the phonon wave vector and $\epsilon_{sc}^2(q_\parallel,k_F)$ is a screening factor. This expression for P is written in a modified form[13] from that in Ref. 7 and also includes a screening term omitted in Ref. 7.

The frequency-dependent part of the integrand includes four terms (i) the "blackbody" term $q^4 n_{qs}(T_e)$ which has a maximum at phonon energies $\hbar\omega \sim 3.8 k_B T_e$, (ii) the term $G(q,\theta)/q_\parallel$ which limits the emission to wave numbers q for which $q_\parallel < 2k_F$ where k_F is the Fermi wave number $[k_F=(2\pi n_s/g)^{0.5}]$, (iii) the bound-state form factor $F(q_z)$ which requires $q_\perp < a^{-1}$ where $a^{-1} \sim n_s^{1/3}$ (a is the effective width of the 2DEG and $q_\perp$ is the normal component of the phonon wave vector), and (iv) ϵ_{sc} the screening term which depends on $q_\parallel$ and k_F. Under the conditions of the present work, $k_B T_e \gg 2\hbar v_s k_F$ where v_s is the sound velocity and the maximum of the blackbody distribution lies well above the cutoff frequencies of terms (ii) and (iii). So the emission is controlled by these last two terms (the screening term significantly reduces P but has less effect on the n_s dependence of its frequency distribution) with the result that there should be an increase in the proportion of high-frequency phonons when n_s is increased at constant T_e or power rather than the decrease observed experimentally. This is illustrated by numerical integration of (1) as shown in Fig. 5 for $P=20$ mW mm^{-2} for two values of n_s; the modest changes attributable to screening, in the n_s dependence of the frequency distribution, are shown elsewhere.[14]

In fact, as we have seen there is clear evidence from resistance measurements that significant occupation of an excited subband or bands is occurring at these power densities. In the range of n_s explored here, as n_s is increased, the power P_m needed to produce significant occupation fell[5] indicating that the density of excited electrons should increase if the power is kept constant. These electrons have a much lower Fermi wave number and are more weakly confined than the electrons in the ground subband so they emit phonons of lower frequency (lower $q_\parallel$ and $q_\perp$) through intraband transitions than those from the ground subband and this should also be the case for intersubband intravalley transitions. The situation is less clear, however, for the high-frequency emission from intervalley transitions associated with the E_0' states. The increasing occupation of E_0' with n_s should lead to an increase in this emission and its decay products while the fall in electron temperature with n_s should lead to a decrease.

We conclude that the shift in the phonon spectrum to lower frequencies as n_s is increased can be attributed to the increasing proportion of excited electrons. The emission from intervalley transition would appear either to be rather weak or to fall in intensity with n_s as a result of the decreasing electron temperature.

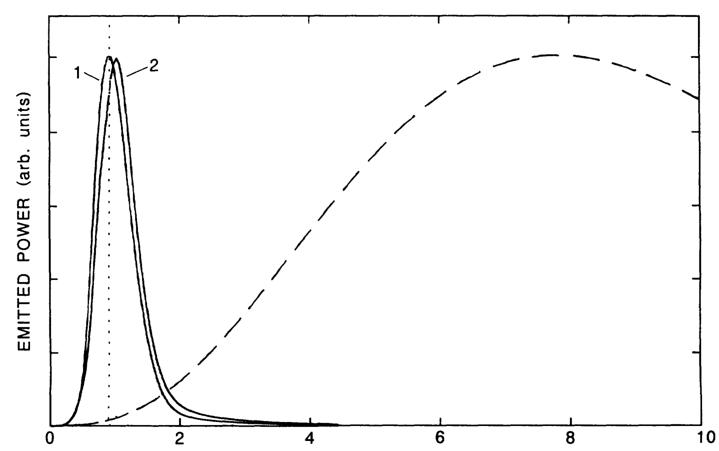

FIG. 5. Calculated phonon spectra (solid lines) emitted from a heated 2DEG with input power density $P=20$ mW mm^{-2}: (curve 1) $n_s=1.6\times10^{16}$ m^{-2}, $T_e=109$ K; (curve 2) $n_s=3.2\times10^{16}$ m^{-2}, $T_e=89$ K. The dotted line shows the frequency threshold of the exciton cloud phonon detector. The dashed line indicates the blackbody distribution for $T=100$ K, showing that its peak lies well above those of the calculated distributions at similar temperatures.

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