Detection of Heat Pulses by the Two-Dimensional Electron Gas in a Silicon Device

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A silicon metal-oxide semiconductor field-effect transistor has been used to detect heat pulses generated by electrical heating of a thin metal film. In the presence of a quantizing magnetic field deep oscillations in the detected intensity are observed, the signal being a maximum when the Fermi level coincides with a Landau level. The appearance of an intermediate signal at higher heater temperatures is attributed to cyclotron phonon absorption. We show that this system can be used as a tunable phonon spectrometer.

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Phonon-emission and absorption or scattering by a two-dimensional electron gas (2DEG) in the Si inversion layer has been observed in a number of relatively recent experiments.[1-3] Interesting features associated with the reduced dimensionality of the electron system were observed, such as the $2k_F$ cutoff in the parallel component of the emitted phonon wave vector and the restriction of the phonon emission to small angles relative to the normal to the plane of the 2DEG. In the presence of a quantizing magnetic field, oscillations in the phonon scattering and evidence of cyclotron phonon emission were observed.[4,5] All these experiments give more direct information regarding the electron-phonon interaction in such systems than can be obtained by, for example, measurements of the mobility as a function of temperature.

In the transmission experiments, up to 6% of the normally incident phonon flux was found to be either scattered or absorbed but we were unable to separate these proportions. The present experiment was devised to measure the absorption directly through the rise in temperature of the 2DEG produced by the incident phonon pulse. To do this we used the metal-oxide semiconductor field-effect transistor (MOSFET) previously employed in our emission experiments as a bolometer to detect the heat pulse produced by electrically exciting a metal film.

Our device was an enhancement-mode MOSFET fabricated on the (100) face of a 5-mm-thick 1000-$\Omega\cdot$cm Si wafer. The device gate area was 1×1 mm^2, and the 4.2-K mobility deduced from the Shubnikov–de Haas oscillations was approximately 4500 cm^2/V s. A 1-mm^2, 50-Ω Constantan heater was deposited on the back face of the wafer opposite the MOSFET. The sample was held at a temperature of 4.2 K in a helium cryostat; fields up to 7 T could be applied normal to the plane of the 2DEG. Electrical pulses of 100 to 200 ns duration and power densities in the range 0.5 to 10 W mm^{-2} were applied to the heater. Changes in the channel resistance, R_{DS}, produced by the phonon pulses were detected by our passing a 100-μA bias current through the MOSFET and observing the voltage pulses across the drain-source electrodes which were connected to a high-impedance amplifier. The amplified signal was fed to a signal-averaging system based on a digital storage oscilloscope and a microcomputer.

In Fig. 1 we show typical voltage pulses from R_{DS} obtained with the above setup. The degenerate transverse modes are clearly resolved; it is of note that the maximum in the detected signal occurs 100 to 200 ns later than the phonon time of flight across the sample depending on the heater pulse length, showing that the MOSFET is integrating the incident phonon pulse. We were unable to see a longitudinal mode, suggesting very weak coupling between the 2DEG and longitudinal-mode phonons. In order for phonon absorption or scattering by a 2DEG to occur, it is essential for the phonon to have a wave-vector component, $q_{\parallel}\leq 2k_F$, in the plane of the 2DEG. In the chosen geometry such a component arises as a result of the complicated shape of the transverse-mode slowness surface near the [100] direction in silicon. In the case of the longitudinal mode the slowness surface is nearly spherical; hence, there is little or no wave-vector component in the plane which explains the absence of any signal corresponding to the longitudinal mode.

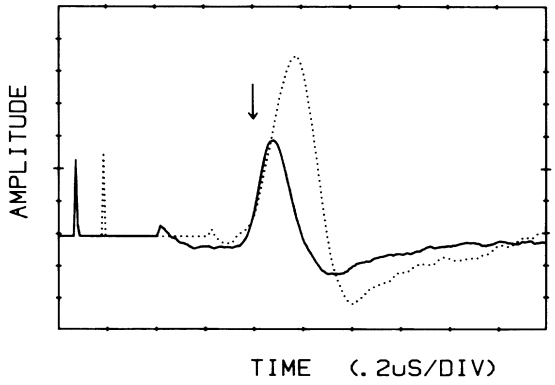

FIG. 1. Heat-pulse signal detected by Si MOSFET for 100 ns (solid line) and 200 ns (dotted line) heater pulse lengths. The power input was 2.5 W mm^{-2} in both cases. The arrow indicates the expected time of arrival of the ballistic pulse.

The sign of the signal indicates that the phonon pulse causes an increase in R_{DS}, and so a decrease in electron mobility. The device has its maximum sensitivity at a gate voltage $V_G \simeq 12$ V, irrespective of heater input power, followed by a steady decrease to zero at $V_G > 100$ V. We also performed measurements of the temperature dependence of R_{DS} in the region of 4.2 K and found that dR_{DS}/dT was positive and its magnitude depended on gate voltage in a similar way to the sensitivity. At the chosen operating point $dR_{DS}/dT = 40\ \Omega\ K^{-1}$. On the basis of this calibration we were able to deduce that the increase in the 2DEG temperature produced by a 100-ns, 2.5-W$\cdot$mm^{-2} pulse was 0.34 K. This increased to 0.66 K for the 200-ns duration pulse showing that little of the absorbed energy is reradiated on this time scale.

If the decrease in mobility were due to direct scattering by the phonons in the pulses, then the detected signal would not increase in proportion to the pulse length as observed. It seems reasonable, therefore, to attribute it to an increase in the 2DEG temperature together with the temperature-dependence screening of the oxide charge scattering.[6] We have considered two models to account for this temperature rise: One possibility is that the phonon pulse is thermalized at the interface between the substrate and the gate oxide layer and is warming the electrons by virtue of their close proximity. The other is that the electrons are heating up by absorbing the phonons directly. By considering our sample geometry and phonon focusing effects, we estimate that approximately 1/40 of the total phonon energy is incident on the MOSFET. The oxide layer is topped by an aluminum gate which has a high thermal conductivity compared with the oxide and it is in direct contact with the liquid helium; this all acts to pin the top side of the oxide layer at 4.2 K. A temperature gradient ΔT is established across the oxide layer by thermal conduction, $\Delta T = Q\Delta x/KA$, where Δx is the oxide thickness which is 800 nm for our device, A is the gate area, and K the thermal conductivity of SiO$_2$ which is approximately 20 W m^{-1} K^{-1}. If we were to assume that the entire pulse was thermalized at the interface then for a 2.5-W$\cdot$mm^{-2} heater input $\Delta T \simeq 3$ mK. This is inconsistent with the measured temperature increase. It seems more reasonable therefore to attribute the temperature increase to direct absorption by the electrons: The specific heat capacity of the 2DEG in a Si MOSFET at 4.2 K is approximately 2.5×10^{-8} J K^{-1} m^{-2}, i.e., 2.5×10^{-14} J K^{-1} for our device. This means that for a 100-ns, 2.5-W$\cdot$mm^{-2} pulse only about 10^{-6}% of the incident phonon energy is absorbed by the 2DEG to give the measured temperature rise.

We observed a very different behavior in applying a magnetic field: Figure 2 compares the variation of the absorbed energy with the Shubnikov-de Haas oscillations in R_{DS} and V_G was swept in a constant field of 7 T. The carrier concentration and so the Fermi level, E_F, are proportional to the gate voltage; therefore, by sweeping V_G we can scan E_F through the Landau-level spectrum. The results obtained with a 0.5-W$\cdot$mm^{-2} heater input show that the absorption has a maximum when E_F coincides with a Landau subband and becomes very small when E_F lies between two. This suggests that the absorption is by intra-Landau-level electronic transitions and has similar characteristics to the zero-field case. At an increased heater input a smaller signal was clearly observed between the main peaks; the drain-source voltage pulse associated with this signal is shown in Fig. 3. It is not delayed in time like those in Fig. 1 but peaks at a time equal to the phonon time of flight following the excitation pulse. We see that its amplitude is a maximum when E_F lies midway between two Landau levels. The signal is attributed to the absorption of cyclotron-frequency phonons associated with inter-Landau-level electronic transitions.

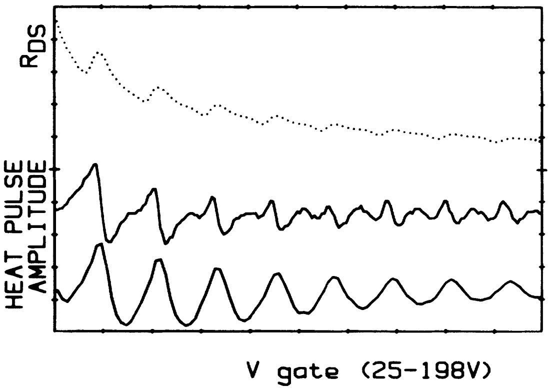

FIG. 2. Variation of detected signal amplitude with gate voltage at $B = 7$ T for two heater power input levels, P_{in}: upper trace $P_{in} = 5$ W mm^{-2}, lower trace $P_{in} = 0.5$ W mm^{-2}. Shown also for comparison are the Shubnikov-de Haas oscillations in the drain source resistance (dotted line).

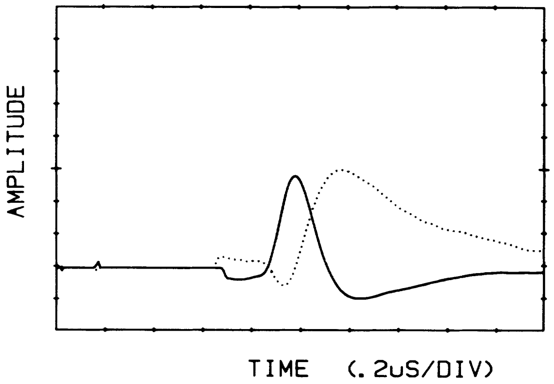

FIG. 3. Heat-pulse signal detected at $B = 7$ T for E_F between the Landau subbands (solid line). Heater power input 5 W mm^{-2}, pulse length 100 ns. The dotted line shows the signal (not to scale) observed when E_F coincides with a Landau subband.

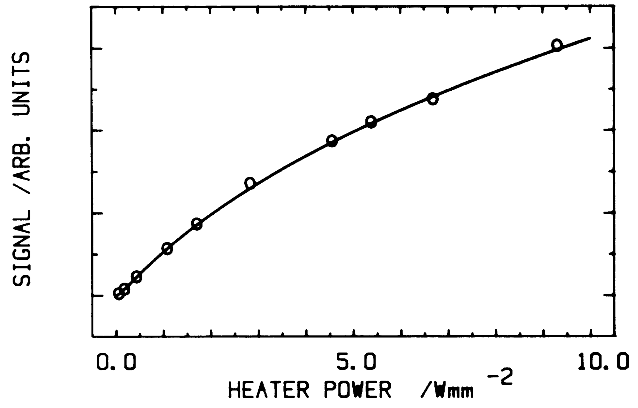

FIG. 4. Amplitude of inter-Landau-level signal at $B=5$ T as a function of heater input power. The solid line is calculated by assumption of a blackbody heater spectrum and use of acoustic mismatch theory.

The phonon absorption is a maximum when the Fermi level is coincident with the maximum of the function $f_1(1-f_2)$ where f_1 and f_2 are the Fermi factors for the initial and final electron states of energy E_1 and E_2, respectively. The maximum of this function is clearly at $(E_1+E_2)/2$; therefore, when E_F is midway between two Landau levels the absorption rate is a maximum for cyclotron-frequency phonons $\omega_c=(E_2-E_1)/\hbar$.[7] At high heater excitation powers, the proportion of high-energy cyclotron phonons in the heat pulse is increased which accounts for the observation of the intermediate peak only at these levels. The transfer of an electron from a full to an empty Landau level contributes instantly to a change in the 2DEG conductivity and consequently there is no time delay in the observed heat pulse signal.

We next investigated the possibility of using this system as a frequency-selective phonon detector. A field of 5 T was applied and the gate biased to put E_F between two Landau levels so that the system responded to cyclotron-frequency phonons. The size of the absorption peak was then measured as a function of heater excitation power, Fig. 4. If we assume a "blackbody" heater spectrum, the phonon power, $P_e(\omega)$, emitted in the spectral range ω to $\omega+d\omega$ is given by

$$P_e(\omega)=\mathrm{const}\times\omega^3\left[\frac{1}{\exp(\hbar\omega/kT_h)-1}-\frac{1}{\exp(\hbar\omega/kT_0)-1}\right].$$

The heater temperature T_h is related to the total electrical power input: $P_\mathrm{in}=\sigma(T_h-T_0)$ W m^{-2}, where the constant σ depends on the acoustic mismatch between the heater and the silicon substrate. The solid line through the data in Fig. 4 was obtained by evaluation of this expression at a frequency $\omega=\omega_c=eB/m^*=4.6\times10^{12}$ s^{-1}. To fit the line to the data we needed a value of $\sigma=150$ which is in good agreement with the value of 160 obtained from acoustic-mismatch theory.[8]

In conclusion we have found that a very small fraction of the ballistic phonon pulse is absorbed by the 2DEG. The significant rise this produces in the electron temperature is due to the small specific heat of the 2DEG and this in turn produces an appreciable change in R_DS which is consistent with steady-state measurements of R_DS as a function of temperature. Furthermore, we have demonstrated that a Si MOSFET in a magnetic field can be used as a frequency-selective phonon detector, the frequency bandwidth being dependent on the Landau-level width, which is about 300 GHz in this case.

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