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Voltage-Tunable Far-Infrared Emission from Si Inversion Layers

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We have observed voltage-tunable far-infrared emission from inversion layers of n-channel metal-oxide-simiconductor field-effect transistors fabricated on p-type (100) Si. The radiation is emitted by the electronic transition from the two-dimensional excited-state E_1 sub-band of the inversion layer to its ground-state E_0 sub-band. Population of the excited-state sub-band is realized by heating up the electron distribution with an electric field applied along the channel.

In the inversion layer of a Si-MOS (metal-oxide-semiconductor) structure, the energy levels of the electrons, being discrete for their motion perpendicular to the interface and continuous for their motion parallel to the interface, form two-dimensional sub-bands.[1] There has been great interest in the problem of the sub-band splitting, which is a function of the electron density n_s in the inversion layer and also dependent on the impurity concentration of the Si substrate. Experimentally, far-infrared absorption[2] and photoconductivity experiments[3,4] have been performed to measure the sub-band splitting. We note especially the absorption experiment of Kneschaurek and co-workers[2] and the photoconductivity experiment of Wheeler and Goldberg[3] on the (100) Si inversion layers. The results from these two experiments are in disagreement. While Kneschaurek and co-workers observed one resonance line in their absorption spectra, Wheeler and Goldberg observed two photoresistive peaks: one broad peak at the resonant absorption energy and a sharp peak at a lower energy. The resonance energy and its n_s dependence from either experiment disagree with the energy splitting between the ground-state sub-band E_0 and the first excited-state sub-band E_1 as predicted by the self-consistent field calculations of Stern.[5] Subsequent theoretical work[5-8] has shown that the many-body corrections in this system are sufficiently large to account for such discrepancies between theory and experiment. More recently, however, the importance of screening of the electromagnetic field by the inversion-layer electrons has been recognized.[9,10] It also changes the resonance condition and shifts the resonant energy appreciably above the sub-band splitting.

In view of the complexity of this problem and the great current interest in it, we have performed an experiment to measure the far-infrared radiation emitted by electronic transitions between the sub-bands. We used n-channel Si-MOSFET's (metal-oxide-semiconductor field-effect transitors) on p-type (100) Si and populate

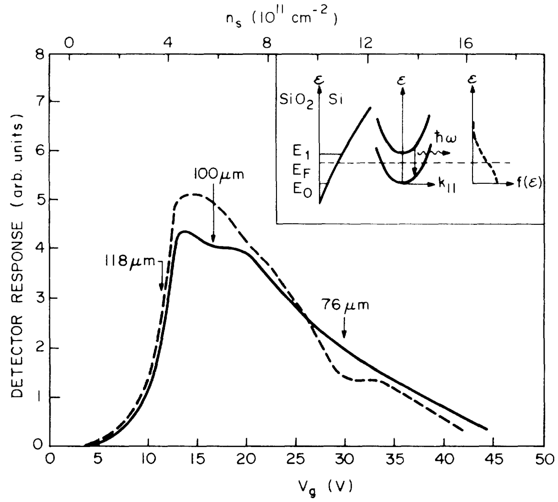

FIG. 1. The detector response versus V_g when an electric field, $E_D = 20$ V/cm, is applied along the inversion layer of the Si-MOSFET at 4.2 K. The full curve was taken with a 2-mm-thick Ge:As filter; and the dashed curve, with a 4-mm-thick crystal quartz filter. The inset illustrates the energy structure of the Si inversion layer and the radiative transition between E_1 and E_0 sub-bands. $f(\epsilon)$ is the electron distribution function.

the excited-state sub-band by heating up the electron distribution[11] with an electric field along the channel. (An illustration of the energy structure of the Si inversion layer and the radiative process is shown in the inset of Fig. 1.) We have observed narrow-band far-infrared radiation which can be tuned simply by varying the gate voltage (V_g) on the Si-MOSFET's. As far as we know, this is the first observation of radiative decay of electrons in surface states. In the rest of this Letter, we shall describe this experiment, present the results, and discuss them in relation to the energy structure of the Si inversion layer and the far-infrared absorption and photoconductivity experiments.[2,3]

The gate oxide of the Si-MOSFET's were thermally grown at 1100°C and subsequently annealed in H_2 at 380°C. We have studied samples made on 6–12 Ω-cm Si substrate, with oxide thickness varying from 0.1 to 1.0 μm and the peak mobility of the inversion layer at 4.2 K varying from 8000 to 20 000 cm^2/Vsec, and have obtained the same results. The data presented in this Letter were obtained from devices on 10 Ω-cm Si substrate with a 20 000-cm^2/Vsec peak mobility at 4.2 K. The gate area of these devices is either 2.5×2.5 mm^2 or 0.25×0.25 mm^2. The emission measurements were made at 4.2 K and no dependence on T was noticed by going down to 1.6 K. The sample and the detector were mounted in a brass light pipe with closed ends so that all the emitted radiation could be collected onto the detector. The radiation was generated by heating the inversion-layer electron gas with a drain voltage V_D, which was pulsed with 1-msec to 1-μsec pulse length and 1/20 or 1/100 duty cycle to avoid sample heating. The emitted radiation was detected by a photoconductive gallium-doped germanium (Ge:Ga) detector with a well-known spectral response[12] and analyzed by using narrow-band filters placed between the sample and the detector. The detector response was measured by a boxcar integrator and plotted directly as a function of V_g. The inversion layer n_s was determined from V_g by using $n_s = C_0(V_g - V_t)/e$, where C_0 is the oxide capacitance per square centimeter, V_t is the conduction threshold of the channel at 78 K, and e is the electronic charge. We also studied the Shubnikov–de Haas oscillations of these samples and thereby obtained the same values for V_t and C_0/e.[13]

It should be noted that, with the devices having a 2.5-mm channel length, the V_D required to generate sufficiently intense radiation from the inversion layer can be an appreciable fraction of V_g. When this is the case, the detector signal becomes dependent on the polarity of V_D and it is necessary to take the average of the detector signal for the two V_D polarities. We find that, if this averaged signal is plotted as a function of V_g, it always yields a detector-response spectrum identical to that obtained from devices having channel length ten times shorter. On such devices, V_D can be kept less than 10% of V_g and the detector signal is independent of the polarity of V_D.

Figure 1 shows the detector response and its dependence on n_s in the inversion layer (or V_g on the device) when an electric field along the channel, $E_D = 20$ V/cm, is applied to the Si-MOSFET. The full curve was taken with a 2-mm-thick Ge:As filter and the dashed curve was taken with a 4-mm-thick crystal quartz filter. No signal was detected when the polarity of V_g was reversed. Qualitatively, these curves reflect the spectral response of the Ge:Ga detector,[12] indicative of narrow-band emission tunable by changing V_g on the device. These features are more quantitatively demonstrated by the use of narrow-band filters. The crystal quartz filter has a sharp absorption peak at 76 μm[12,14] and the Ge:As filter has a sharp absorption peak at 100 μm.[15] These absorption peaks are clearly resolved at $V_g = 30$ V and at $V_g = 16$ V, respectively, in Fig. 1. The spectral response of the Ge:Ga detector itself has a relatively sharp cutoff on the long-wavelength side,[12] which is also resolved at $V_g \simeq 12$ V. For $E_D \lesssim 30$ V/cm, we estimate, from the results with the quarts filter, one single emission line with a linewidth ~6 cm^{-1}. At higher E_D, the emission line broadens and a shift of the detector response to lower V_g becomes apparent for $E_D \gtrsim 80$ V/cm. This shift may be indicative of shorter-wavelength contributions.

The emission intensity at 100-μm wavelength, for a 2.5×2.5-mm^2 gate device, is estimated to be ~3×10^{-12} W when $E_D = 20$ V/cm. The intensity increases approximately hundredfold when E_D is increased to 100 V/cm. Figure 2 shows the E_D dependence of the relative intensity of the emission at two different inversion-layer densities from two devices. The circles (⊕ and ⊗) are data from the device with a 2.5×2.5-mm^2 gate; and the crosses (+ and ×) are the data (multiplied by 100 to correct for the difference in area) from a 0.25×0.25-mm^2 gate device. For $E_D \gtrsim 30$ V/cm, we also studied the decay time of the emission after E_D is turned off. We find that the emission decays faster than our detector response time, which is ~10^{-6} sec, indicating a hot-electron relaxation time shorter than 10^{-6} sec. We also measured the channel mobility of our samples as a function of E_D and as a function of the sample temperature T. For $n_s \gtrsim 6\times10^{11}$/cm^2, we observe a continuous decrease of mobility with increasing T (for $T > 5$ K). This result suggests lattice scattering as the dominant relaxation mechanism in our samples.

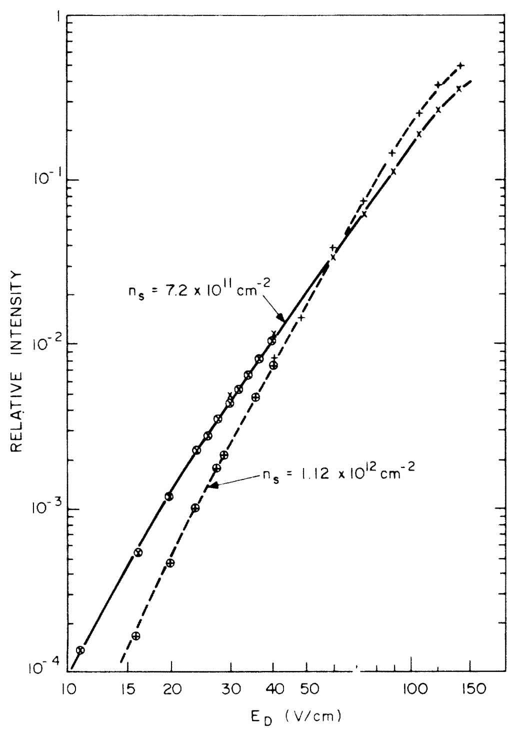

FIG. 2. The relative intensity of the emitted radiation as a function of the electric field along the channel at two densities. The circles (⊕ and ⊗) are data from a 2.5× 2.5-mm^2 gate device and the crosses (+ and ×) are the data (multiplied by 100 to correct for the difference in gate area) from a 0.25× 0.25-mm^2 gate device.

On a Si (100) surface, the inversion layer has two sets of sub-bands,[1] namely, the light-mass E_0, E_1, ... sub-bands derived from the [001] and [00$\bar{1}$] conduction ellipsoids, whose long axes are perpendicular to the Si-SiO$_2$ interface, and the heavy-mass E_0', E_1', ... sub-bands, derived from the other four conduction ellipsoids of Si. It has been known that E_0 lies lowest in energy and that E_1 lies above E_0'.[13,16] The observed far-infrared radiation is emitted by electrons in the E_1 sub-band as they relax into the E_0 sub-band. Direct transition from E_0' to E_0 is not allowed. If we assume the inversion layer to be 100-Å thick, the three-dimensional electron density of this layer at $n_s = 10^{12}$/cm^2 is 10^{18}/cm^3 and its absorption coefficient, estimated from Stern's calculation,[17] is $\alpha \approx 260$ cm^{-1}. The Einstein coefficient and the emitted power can be estimated[18] from the energy ϵ of the emission line, its linewidth $\Delta\epsilon$, and the temperature T_e of the electron gas. Estimating that $T_e = 25$ K and using $\epsilon = 14.5$ meV and $\Delta\epsilon = 0.8$ meV, we obtain for the 2.5×2.5-mm gate device the emitted power at $n_s = 10^{12}$/cm^2 to be ~5×10^{-11} W, in agreement with our observed intensity with $E_D \approx 50$ V/cm. In this same electron temperature range, population in the E_2 and E_1' sub-bands is expected to be much less than 1% of the population in the E_1 sub-band. Such small population alone makes it clear that this experiment is not expected to resolve the E_2-to-E_0 or the E_1'-to-E_0' transitions.

In Fig. 3 the emission energy is plotted as a function of n_s together with those from the absorption and the photoconductivity experiments[2,3] (the data points on the broad photoresistivity peak in the experiment of Wheeler and Goldberg are omitted for the sake of clarity). The solid curve is the sub-band splitting between E_1 and E_0 (for Si substrate doping $N_A - N_D = 7\times10^{14}$ cm^{-3}) from Stern's calculations[6]; and the dashed curve is the far-infrared resonance energy for transitions between E_1 and E_0 when inversion-layer screening of the radiation field is taken into account.[10] It is

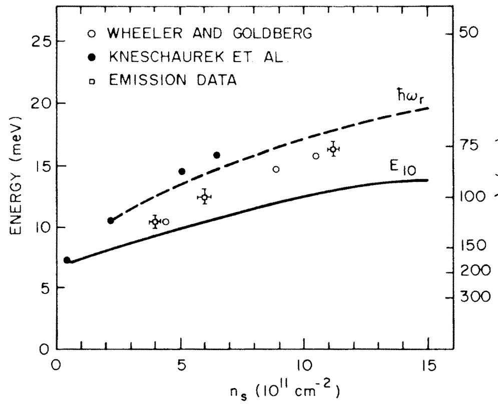

FIG. 3. The emission energy versus n_s together with the absorption data from Kneschaurek and co-workers (Ref. 2) and the photoconductivity data of Wheeler and Goldberg (Ref. 3). The solid curve is the sub-band splitting (E_{10}) between E_1 and E_0 from Stern's calculation (Ref. 6) and the dashed curve is the far-infrared resonance energy ($\hbar\omega_r$) when inversion-layer screening of the radiation field is taken into account (from Ref. 10).

apparent that the emission data are in good agreement with the photoconductivity data and that the discrepancy between these data and the absorption data is beyond experimental uncertainties. We should note that while the emission and the photoconductivity experiments employ fully processed Si-MOSFET's, the absorption experiment uses Si-MOS capacitors and creates the inversion layer at low temperatures by using visible light. Although the starting material of p-type Si in all these cases is close to $\rho \sim 10$ Ω-cm, the impurity doping and consequently the depletion-layer field near the Si-SiO_2 interface in the resulting devices may differ considerably from that based on the impurity doping in the substrate. The above-mentioned discrepancy can be removed by postulating that the depletion-layer field near the interface in the MOSFET's is weaker than that in the MOS capacitors. Whether such a postulation is valid can be resolved by further experiments measuring absorption and photoconductivity or absorption and emission of the inversion layer on the same devices.

In this experiment, tuning of the emission was observed from ~130 to ~60 μm with n_s from ~1.5 $\times 10^{11}/\mathrm{cm}^2$ to ~$1.5\times 10^{12}/\mathrm{cm}^2$ by using the Ge:Ga detector. Since the sub-band splitting is a continuous function of n_s and substrate doping, tuning from ~300 to ~15 μm is expected for the radiation from the E_1-to-E_0 transition.[5,17] Transitions from other sub-bands and the use of hole, as well as electron, inversion and accumulation layers on other Si surfaces can extend this tunable range even further.

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