fluctuation energy in the dispersion relations of the collective modes in quiescent plasmas is thus justified.

When the plasma is in a strongly turbulent state, the energy spectrum is enhanced so that $\mathcal{E}_{\vec{k}} \simeq \langle \frac{1}{2} m v^2 \rangle n k^{-3}$ in the same wave-number domain. We thus find that the effects of turbulent fluctuations on the dispersion relation, described by the last term of (9) or (10), become as strong as those produced by the remaining terms; a significant modification of the real frequency of a collective mode takes place in a turbulent plasma. Furthermore, an anisotropy of the spectral distribution $\mathcal{E}_{\vec{k}}$ in $\vec{k}$ space, if such exists, should be reflected in the anisotropy of $\omega(\vec{q})$ through (9) or (10). In conclusion, we have shown that an experimental investigation of the dispersion relation of a collective mode offers a promising method of probing microscopic properties of turbulent fluctuations in a plasma.

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Cyclotron Resonance of Electrons in an Inversion Layer on Si

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We have observed cyclotron resonance of electrons in an inversion layer on a (100) surface of p-type Si. The effective mass m_c^* is found to be about $0.21 m_0$, compared with a bulk value of $0.1905 m_0$. The surface mass value decreases slightly with increasing gate voltage.

We report the observation of cyclotron resonance (CR) between the Landau levels of the two-dimensional electron gas induced at the (100) surface of a Si crystal with the application of an electric field. Both the electric and magnetic fields are normal to the sample surface, and the experiments are done at the 890.7-GHz frequency (29.71 cm^{-1}) of a far-infrared HCN laser. We measure directly the changes in the absorption of the laser beam traversing the Si sample at near-normal incidence.

The existence of two-dimensional sub-bands of electron states in an n-type inversion layer on a (100) surface of p-type Si has been inferred and demonstrated in various dc transport measurements.[1-7] Particularly interesting and informative are measurements that make use of a magnetic field[1,3,4,7] to quantize the motion of electrons parallel to the surface into a system of two-dimensional Landau levels. Oscillations in the dc conductance along the surface,[1,4,7] and the capacitance of the surface layer,[3] are observed as a function of the surface electron density when a magnetic field exceeding about 10 kOe is applied. This demonstrates clearly the existence of well-defined Landau levels in samples of sufficiently high mobility and when the quantizing magnetic field is strong enough.

Our goal was to observe CR between Landau levels of the surface electron gas, and from such experiments to determine the cyclotron mass m_c^* and scattering mechanisms for electrons bound to within a few tens of angstroms from the surface.[8-10] The position of the CR absorption line defines m_c^* of the surface electrons; the linewidth gives electron lifetime information. Particular interest attaches to a precise determination of m_c^* in order to allow a critical comparison of surface and bulk mass values and to examine if, as has been found from the Shubnikov–de Haas measurements,[7] m_c^* is dependent on surface electron density.

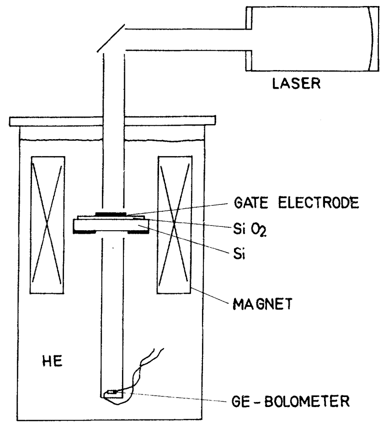

FIG. 1. Experimental arrangement for the observation of far-infrared cyclotron resonance in the space-charge layer of a semiconductor.

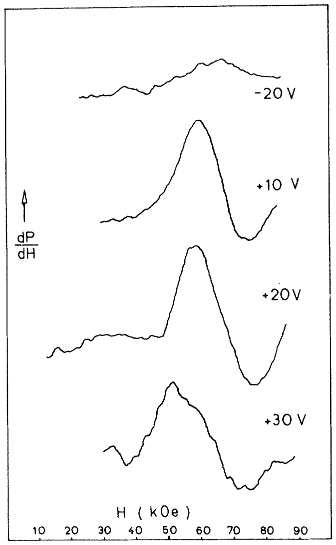

FIG. 2. Cyclotron resonance observed in a p-type Si (100) sample at 890.7 GHz. The recorded signal dP/dH (arbitrary units) represents the magnetic field derivative of power absorbed by the sample. Positive voltages represent an inversion layer polarity. The uppermost trace at $V_G = -20$ V is for an accumulation layer. $T \approx 4.2$K.

The experiments are carried out at high frequency ($\sim 10^{12}$ Hz) and correspondingly high magnetic fields (~ 100 kOe) to achieve the condition $\omega\tau > 1$. We measure directly the absorption of far-infrared radiation, rather than observing the resonance transition indirectly, as for example in a photoconductive response measurement.[11] Direct absorption results, we expect, can be more easily interpreted and evaluated.[10] As in Fig. 1, the sample is mounted directly across the light pipe. The detected signal is the change in the far-infrared energy arriving at the bolometer detector as the magnetic field is modulated. The sample is a (100) slab of p-type Si ($\rho \sim 10$ Ω cm),[12] 0.2 mm thick and covered with approximately 2000 Å of oxide (SiO_2). A very thin (~ 50 Å) layer of a high-resistivity Ni-Cr alloy is evaporated onto the oxide over an area of about 10 mm^2. This film forms the gate electrode. The other side of the gate voltage source attaches to the back side of the sample. We do not use diffused contacts as in the usual metal-oxide-semiconductor field-effect transistor geometry employed in previous experiments. Thus we are able to bias our sample to achieve either an inversion or accumulation surface layer.

Because Si at 4.2°K is a good insulator, and because minority carrier generation is slow, our method of making contact and charging the surface layer had to be verified in separate experiments. We measured the dc capacitance using a vibrating-reed electrometer and a capacitance substitution technique. At low temperatures we found that to charge the inversion layer fully, when there was no light on the sample, required a time of 12 h or more. The same layer was found to discharge very quickly. If the gate voltages were applied prior to cooling down, the surface layer was found to charge immediately. As expected, a small amount of light falling on the sample makes it possible to charge the inversion layer within a few seconds even at 4.2°K. We found that the accumulation layer could be established in a matter of seconds, even in the absence of light and at low temperatures.

In the course of the present experiments the light pipe was blocked with several layers of black polyethylene to prevent any visible light from reaching the sample and thus avoid a signal from bulk electrons. The gate voltages were applied over a long period of time, on the average for more than 6 h, before data were taken. On some occasions the voltage was applied while the sample had not yet been cooled. As we learned later from the capacitance studies, the 6-h period may not have been adequate to bring the inversion layer into equilibrium with the gate voltage. For this reason the quoted values of this voltage are subject to some uncertainty.

We observe CR for the light-mass electrons as in the series of experimental traces in Fig. 2 for various gate voltages V_G. The sample is at ~ 4.2 °K, the experimental frequency is 890.7 GHz, and the magnetic field extends from 0–90 kOe with a modulation amplitude of 1400 Oe peak to peak. No signal is seen at 0 bias voltage. With the same sensitivity, but $V_G = +10$ V, we observe a resonance signal centered at $H_0 = 68.4$ kOe. Increasing the gate voltage to +20 and +30 V yields similar resonances, centered at 66.8 and 64.9 kOe, respectively. These resonance field values represent averages over several traces and are taken as the midpoints between the derivative maximum and minimum. The cyclotron masses at 10, 20, and 30 V are determined as $0.215m_0$, $0.210m_0$, and $0.204m_0$, respectively (m_0 is the free-electron mass).

Judging from the variations between repeated runs, we estimate that the relative error of these mass values does not exceed $\pm 0.003m_0$. It appears that there is a small shift of the effective mass to lower values with increasing gate voltage. This is consistent with the shift found in Shubnikov-de Haas experiments.[7] An estimate of the absolute error in our mass values must include the uncertainty in the interpretation of the line shape and the calibration error in the applied magnetic field. The absolute error, we estimate, could be as much as $\pm 0.01m_0$. Nevertheless, it seems that the surface cyclotron-mass value is higher than the generally accepted bulk value of $0.1905m_0$.[13] The observed relative linewidth $\Delta H/H_0$, where ΔH is the separation of maximum and minimum in the derivative curve, is 0.29 at $V_G = +20$ V. Taking the usual semiconductor CR line shape this would be equivalent to an $\omega\tau$ value of 4.0. Expressed as a mobility this yields 6300 cm^2/V sec, which is typical for (100) Si n-type inversion layers and gate voltages as used in our experiments. We note a small increase of relative linewidth with increasing V_G, a result which is consistent with field-effect-mobility measurements.

The uppermost trace in Fig. 2 shows that with negative bias voltage, i.e., for a p-type accumulation layer, no resonance signal is observed with the same experimental conditions. In the absence of the magnetic field we find an absorption signal for both accumulation and inversion polarity of the gate voltage.

In spite of the uncertainty associated with the value of surface-charge density, we believe we have seen a slight shift to lower mass with increasing surface-charge density. The shift seems to be larger than estimated experimental uncertainties. Whether or not this shift is due to the electron-electron interaction, as had been suggested by Smith and Stiles,[7] remains an unresolved question. Kohn[14] has argued that CR, under conditions where the exciting rf field interacts uniformly with the orbiting electron, gives an effective mass that is not enhanced by the electron-electron interaction. This should be the case here. One possible reason for a difference between a de Haas-van Alphen mass and the one measured in high-frequency CR is the electron-phonon interaction. For the present case, where there seems to be good agreement in the two mass values, we are led to conclude that this effect must be insignificant.

Evidently additional and more detailed CR experiments are needed, and should contribute to a resolution of this and other questions. Our intent at present was to show that CR in a semiconductor space-charge layer can be observed. We are planning several improvements in the experiment and hope that this will lead to more accurate values of m_c^* and $\omega\tau$. This in turn would allow us a more critical study of the gate-voltage dependences that were observed in this work.

It has been brought to our attention that experiments similar to ours have been carried out by a group at the Bell Telephone Laboratories. Their results appear in the following Letter.

We wish to thank Gerhard Dorda of the Siemens Laboratories in München for supplying the samples and advising on sample preparation and characterization. Avid Kamgar provided some of the expertise in the construction and operation of the HCN laser used for the experiments.

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Far-Infrared Cyclotron Resonance in the Inversion Layer of Silicon

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Cyclotron resonance in the n-type inversion layer of silicon has been observed at 4.2°K for electron densities between $(0.38$ and $9.0) \times 10^{12}/\mathrm{cm}^2$. The electron mass is $m^* = (0.20 \pm 0.01) m_0$ and independent of electron density. The far-infrared mobility decreases monotonically as the electron density increases, in marked contrast to the dc mobility which exhibits a strong maximum in the same range of electron concentrations.

In the surface space-charge layer of a semiconductor, quantization of the electronic motion normal to the surface gives rise to a series of sub-bands, each of which is a two-dimensional continuum of energy levels. Such electronic surface states have been observed in the inversion as well as accumulation layers of a large number of semiconductors.[1] In particular the Si inversion layer has been shown to be an interesting model system for studying the interface properties as well as the scattering processes in a two-dimensional electron gas. We note the recent work of Smith and Stiles[2] and Lakhani and Stiles,[3] who extract from Shubnikov-de Haas (SdH) oscillations an electron mass and a g factor which increase at low electron density. This increase has been attributed to electron-electron renormalization of the mass and g factor.[4,5]

In this paper we report the first observation of electron-cyclotron resonance in the n-type inversion layer of a (100) oriented silicon surface, at 4.2°K, with electron densities in the inversion layer from $(0.38$ to $9) \times 10^{12}/\mathrm{cm}^2$. The results are most interesting when compared with the transport parameters obtained from dc measurements on the same surface. The resonance experiments show that the cyclotron mass is essentially independent of electron density, in contrast to the SdH mass which increases at low densities. Further, unlike the dc drift mobility at 4.2°K, that falls rapidly at low electron densities,[6] the far-infrared mobility, obtained from the resonance experiment, continues to rise at the lowest electron densities at which it has been measured.

The experiments were performed on the linear metal-oxide-semiconductor field-effect transistor (MOSFET), Fig. 1, which is fabricated on the (100) surface of 10 000 Ω cm p-type silicon wafers, 0.3 mm thick. The oxide was thermally grown to a thickness of 4100 Å. The gate area was $2.5 \times 2.5\ \mathrm{mm}^2$. In order to pass the far-infrared radiation, the thickness of the gate electrode was reduced, leaving ≈100 Å of Ti metal with a dc surface resistance of 210 Ω/sq.

The cyclotron resonance between the laser radiation and the inversion layer electrons is detected by measuring the change in the reflectivity of the MOSFET when electrons are introduced into the surface channel. The reflectivity is measured with a homodyne detector formed by a Michelson interferometer shown in Fig. 1. If the inversion layer admittance Y_c is small compared with the substrate admittance, the change in detected power produced by introducing electrons into the inversion layer will be given by the sum of two terms,

$$\Delta P \propto A[\mathrm{Re}(Y_c)\cos\varphi + \mathrm{Im}(Y_c)\sin\varphi] + B[\mathrm{Re}(Y_c)\cos\varphi' + \mathrm{Im}(Y_c)\sin\varphi']. \quad (1)$$

The first term in (1) is caused by the small change in reflected radiation beating with the radiation returning from the reference mirror, whereas the second term is caused by beating the same signal with the radiation reflected from the MOSFET substrate. The constants A and B are determined by numerous experimental factors such as losses encountered in transmission to the MOSFET, reflectivity of the MOSFET substrate, multiple reflections from the MOSFET