de Haas—van Alphen effect in silicon inversion layers

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The magnetic susceptibility of Si-inversion-layer electrons was measured for fields up to 15 T. Ideally, the system is expected to become totally quantized with discontinuous magnetization between discrete magnetic levels. In order to detect the small oscillatory magnetic signals (de Haas—van Alphen effect), we have devised a geometry of a metal-oxide-semiconductor field-effect sample structure whose magnetic pickup is directly above the periphery of the gate electrode. The change of magnetization is provided by the modulation of the gate voltage. dM/dn_s for Si(100) inversion layer was measured at 1.5 K for frequencies up to 100 kHz. The detected signals were found to have the expected frequency dependence and the expected spikes between magnetic levels. We also expect quantized steps characterized by integer units of double effective Bohr magneton ($\hbar e/m^*c$) in each magnetic level, which has not been discerned so far with the present sensitivity of the measurements.

The two-dimensional electron gas (2D EG) systems as typified by the inversion layers in Si metal-oxide-semiconductor field-effect transistors (MOSFET's) have been studied extensively.[1] Magnetic quantum oscillations have been studied primarily in the Shubnikov—de Haas effect (SdH) and in oscillations in the capacitance. The recent observation and identification of the quantized Hall effect in these systems[2] has led to much renewed theoretical and experimental interest in this area. The SdH effect is a measure of a nonequilibrium property of the 2D EG. The system is probed under electric field perturbation and understood in terms of current transport. In this paper, we report some preliminary results in the oscillatory magnetization experiments in Si inversion layers.

The oscillatory magnetization in three dimensions, known as the de Hass—van Alphen (dHvA) effect,[3] it is a measure of one of the thermodynamic properties of the electronic system in a quantizing magnetic field. The dynamic scattering process enters in the effect only through the modification of the self-energy. This effect was first successfully explained in a free-electron gas by Peierls.[4]

Consider a 2D EG with an electron concentration n_s (cm^{-2}), the free energy F per unit area in a quantizing magnetic field H for n filled Landau levels and a partially filled $(n+1)$th level at $T=0$ is given by

$$F=E_0 n_s+\sum_{n'=1}^{n}(n'-\tfrac{1}{2})\hbar\omega_c N_L+(n+\tfrac{1}{2})\hbar\omega_c(n_S-nN_L)\ , \tag{1}$$

where n' is the Landau-level quantum index, E_0 is the ground-state energy of the two-dimensional subband, $\omega_c=eH/m^*c$ is the cyclotron frequency for electrons with mass m^* parallel to the surface, and

$$N_L=\xi_{v,s}eH/hc \tag{2}$$

is the density of states of a single Landau level with $\xi_{v,s}$ being the valley and spin degeneracy. For simplicity and without loss of generality, we have ignored spin and valley splitting, temperature, and collision broadenings. The magnetization M is then given by

$$-M=\frac{\partial F}{\partial H}=\sum_{n'=1}^{n}(n'-\tfrac{1}{2}(4\beta^* N_L)-n(n+\tfrac{1}{2})(4\beta^* N_L)+(n+\tfrac{1}{2})(2\beta^* n_s)\ , \tag{3}$$

where $\beta^*=e\hbar/2m^*c$ is the effective Bohr magneton. Figure 1 shows the normalized free energy and magnetization as a function of the normalized electron density n_s/N_L where integers n designate the filling of the particular Landau levels. The kinks in the free energy and the discontinuities in the magnetization at integer values of n_s/N_L, respectively, are the result of the δ-function density of states of the Landau levels in an ideal 2D system.

Since the spin and valley equally divide the Landau level density, these figures represent approximately the well-resolved spin and valley splitting spectra of M if one replaces N_L by eH/hc, and $\omega_c=eH/\xi_{v,s}m^*c$. An analytical account for the spin splitting in a size-quantized 2D system using odd and even integer representations was given by Gurevich and Shik[5] and by Kao *et al.*[6]

Since N_L is about $2.4\times10^{11}\ \text{cm}^{-2}$ for $H=10$ T, for a spin- and valley-resolved level, the total magnetization for a typical sample of $10^{-2}\ \text{cm}^2$ is of the order of 10^{-9} erg/G which is difficult to detect. Störmer *et al.*[7] have approached this problem by stacking GaAs/AlGaAs multilayer heterostructures equivalent to several hundred cm^2 of 2D EG and using a dc superconducting quantum

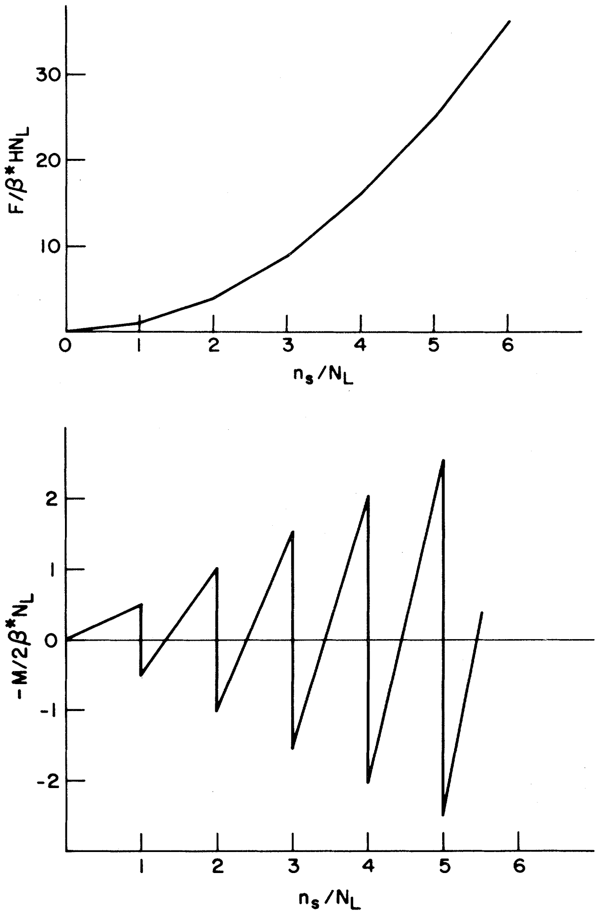

FIG. 1. Normalized electron free energy and magnetization as a function of the normalized electron density n_s/N_L in a constant quantizing magnetic field where the integer n designates the number of filled Landau levels.

interference device (SQUID). We chose to measure the change of M with respect to the carrier concentration n_s.[8] The method is to modulate the gate voltage and measure the magnetically induced signal in a pick-up coil which is placed on the periphery of the gate electrode. Phase detection techniques were employed for the induced signal at modulation frequencies up to 100 kHz.

Figure 2 shows schematically the sample and measurement configurations. The active gate and pick-up coil geometry are shown in Fig. 3. The Si substrate is 100-Ω cm p-type (100). The inversion layer has the shape of twenty 25×500 μm^2 fingers. The gate is n-doped polycrystalline Si. The gate oxide thickness δ_{ox} is 437 Å. Around the inversion layer, the Si wafer is n-type doped degenerately to provide the access for the inversion layer electrons. On top of the gate electrode, there is a 520-Å chemical-vapor-deposited (CVD) oxide layer. The pickup coil surrounds the gate electrode and is 5-μm-wide Al on top of the CVD oxide. On the same wafer, there is a monitoring FET with W and L dimensions equal to 250 and 25 μm, respectively, with the same gate and oxide structure as the dHvA samples.

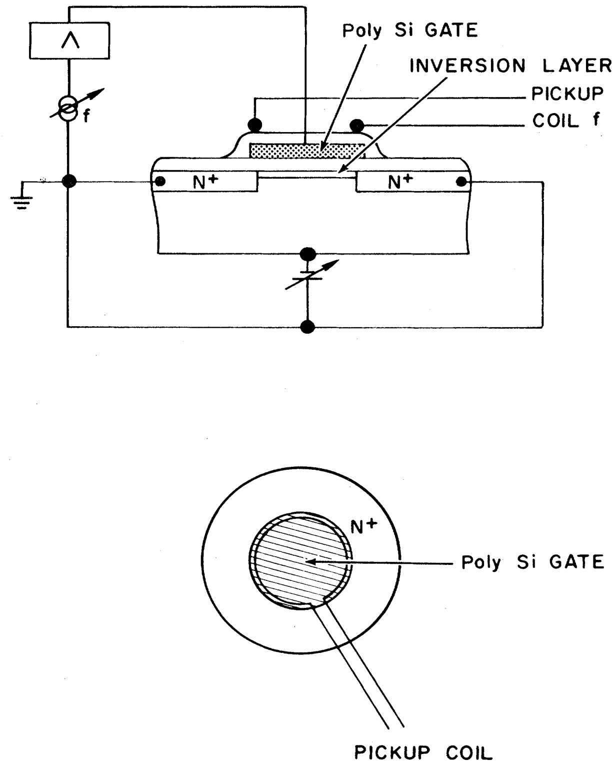

FIG. 2. Schematic diagrams of the sample and measuring configurations.

The dHvA effect is observed as a voltage induced in the pick-up coil due to the time rate of change of the flux induced by the time-dependent magnetization of the inversion layer electrons. We modulate the electron density sinusoidally such that

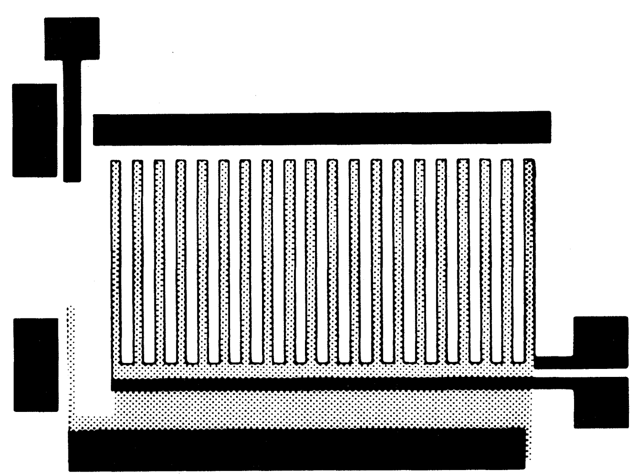

FIG. 3. Gate and pick-up coil geometry of the actual sample. Heavily doped n-type region surrounds the inversion layer under the gate.

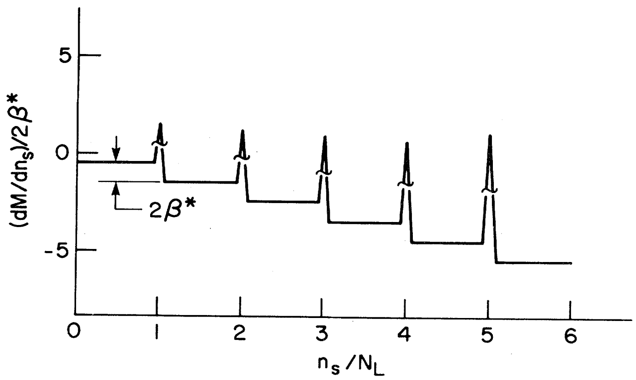

FIG. 4. Schematic of the expected behavior of dM/dn_s as a function of the normalized electron density n_s/N_L in a constant magnetic field.

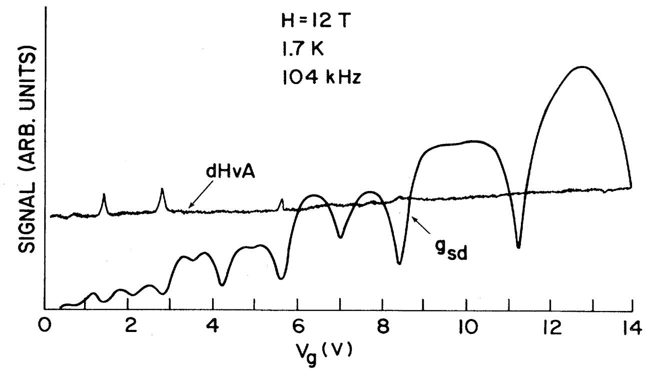

FIG. 5. dHvA detected from the pick-up coil as a function of the gate voltage at $H=12$ T, $T=1.7$ K, and modulation frequency at 104 kHz. Also shown is the SdH oscillation in channel conductance g_{sd} of a companion FET. The expected dHvA spikes between magnetic levels as clearly seen.

$$V(t)=\frac{d\phi}{dt}=\frac{AC_{\rm ox}}{e}\left|\frac{dM}{dn_s}\right|\frac{dV_g}{dt}\ , \tag{4}$$

where A is the total area under the gate, $C_{\rm ox}=\kappa/4\pi\delta_{\rm ox}$ is the specific gate capacitance and V_g is the time varying part of the gate voltage with κ being the dielectric constant of the gate oxide. The primary contribution to the induced voltage is derived from the magnetization of the electrons near the pick-up coil, and the area under the gate. Also it can be shown that for a rectangular-shaped field effect inversion layer structure with the long and narrow dimensions W and L, respectively, the characteristic charging time is proportional to L^2. These are the reasons for the shape of the sample shown in Fig. 3 used for the high-frequency modulation experiment.

We note from Eq. (3) that

$$-\frac{dM}{dn_s}=(n+\tfrac{1}{2})\hbar e/m^*c \tag{5}$$

and the pick-up signal is given by

$$|V(t)|=A(n+\tfrac{1}{2})\hbar C_{\rm ox}\omega V_{g0}/m^*c\ , \tag{6}$$

where ω and V_{g0} are the gate modulating frequency and amplitude, respectively.

A schematic of the behavior of dM/dn_s as a function of n_s/N_L is shown in Fig. 4. We thus expect quantized plateaus in steps of the double effective Bohr magneton, $\hbar e/m^*c$, for each quantum number n.

Typical results for the induced pick-up coil as a function of gate voltage are shown in Fig. 5. The conductance of the monitoring FET is shown also. It can be seen that the spike structure observed in the induced voltage occurs at positions where Landau levels are filled, as expected. The results of a crude check for the amplitude dependence on frequency and modulation amplitude are as expected. The sign of the spike is in the direction of increasing $|dM/dn_s|$ with a relative amplitude in the order of 10^{-8} V. For fixed frequency, the relative size of the different spikes depends on two competing conditions. The first is the increasing size at higher densities as illustrated in Fig. 5, whereas the second is increasing scattering rate with respect to increasing density which is expected to decrease the size at higher densities. As can be seen, the latter dominates the spike structure which disappears completely at the highest densities studied. It can also be seen from Fig. 4 that the plateau structure predicted for the low scattering regime is not observed. Clearly, our present signal-to-noise ratio is not adequate to resolve the quantum step of double effective Bohr magneton.

One concern in such a quasi-dc experiment is that in fact there are frequency effects present. After all, we are charging and discharging a capacitor structure. We are in an open structure geometry and expect that the appropriate resistance for charging the capacitor between Landau layers is the quantized resistance.[9] From the results of the monitoring structure, we can see that the quantized admittance is a linear function of the Landau levels filled. Any charging effect should have a similar dependence. However, it can be seen that the experimental results do not behave in that fashion. We note that the size of the $n=2$ structure is about the same size as that for $n=4$. Further, the $n=6$ is missing while the $n=8$ and 12 are visible. We conclude that although there may be some vestigal effects due to the frequency, such effects cannot be a major cause of the observed structure.

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