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SPIN DEPENDENT TRANSPORT IN A TWO-DIMENSIONAL ELECTRON GAS

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Scattering by neutral impurities in Si has been demonstrated through measurements of spin dependent transport (SDT) in a two-dimensional electron gas (2DEG). SDT was observed by monitoring the conductivity of a specially fabricated Si accumulation layer transistor operating at 4K while modulating the electron spin populations. By utilizing the differences in the singlet and triplet scattering cross sections, the technique provides the first direct measure of neutral impurity scattering A signal from $\sim 10^8$ spins was observed, which demonstrates the enhanced sensitivity of SDT over conventional electron spin resonance methods

ELECTRON transport in semiconductors has been a subject of interest for many years One of the earliest scattering mechanisms to be treated theoretically was neutral impurity scattering, direct experimental evidence, however, has lagged far behind At low temperatures it is expected to contribute significantly to the resistivity of semiconductors doped with shallow impurities In 1949 Pearson and Bardeen[1] noted that the interaction of a conduction electron with a neutral impurity can be treated within the effective-mass approximation, as the scattering of a free electron off a hydrogen atom In the low energy limit, Erginsoy[2] calculated a temperature independent neutral impurity scattering rate, further refinements were made by other investigators[3] Two different groups[4,5] deduced a neutral impurity mobility by subtracting the calculated lattice and ionized impurity scattering rates from the measured Hall mobility

Honig[6] and Schmidt[7] proposed a direct demonstration of neutral impurity scattering by utilizing the difference in singlet and triplet cross sections for scattering of conduction electrons from neutral donors. This difference is due to the requirement of the Pauli principle that the wavefunction of the conduction electron - neutral impurity system be antisymmetric in the coordinates of the conduction and impurity electrons Polarization of the two spin species by an applied magnetic field increases the probability, in a scattering event, of finding the conduction and donor spins parallel, i e , in a triplet state A difference in singlet and triplet cross sections then implies that the electron mobility, and device conductance, will depend upon the degree of polarization of the spins We denote by spin dependent transport (SDT) the dependence of conductance on spin polarization In the presence of DC and microwave magnetic fields, when the Zeeman resonance condition is satisfied there will be a partial saturation of the spin polarization SDT is observed by monitoring the conductivity of a specially fabricated Si transistor, while modulating the electron spin populations using electron spin resonance (ESR) techniques

Early measurements of a spin dependent photoconductivity signal in Si were interpreted as SDT[7,8] but were later shown[9] to be due to the polarization dependence of electron trapping and recombination instead of neutral impurity scattering ESR[10], and other resonant processes have also been indirectly detected via bolometric response of the sample [11] We report here the detection of spin dependent transport (SDT) in a two-dimensional electron gas (2DEG) by directly measuring the scattering of spin 1/2 conduction electrons off neutral impurities, as proposed in references 6 and 7 This experiment employs an equilibrium carrier concentration and electron recombination is not an issue, the bolometric sensitivity of our sample is far too low to be the operative mechanism.

The observation of spin polarization effects in the conductivity presents several experimental challenges The sample needs to be at low temperature to bind the impurity electron to the donor atom, thereby rendering it electrically neutral However, transport measurements must also be made without using photogenerated carriers These competing requirements were satisfied by fabricating a Si metal-oxide-semiconductor field-effect transistor (FET), with an n-channel accumulation layer, that operates at 4K The 2DEG density could be controlled by the gate and the carriers were provided by the degenerately doped source and drain contacts. Therefore we had a variable density of free electrons scattering from a fixed density of neutral impurities A stripline resonator was incorporated as part of the device structure to modulate the electron spin polarization In measuring the transistor current as a function of magnetic field, a resonant change, due to spin dependent scattering $\Delta I/I_o$, is observed when the Zeeman resonance condition is satisfied (see Fig 1)

SDT provides a high sensitivity indirect technique for observing ESR in two or lower dimensional structures. Our present sample contains 10^8 to 10^9 spins within the channel, which would be undetectable using conventional ESR techniques. Since a reduction in the transistor gate area by a factor of 10^4 is not expected to change the device mobility, a SDT signal would easily be observable from 10^4 or fewer spins The enhanced sensitivity of our method is due to the fact that we exploit the effect of spin dependent interactions on the sample conductivity instead of measuring directly the microwave power absorbed by the spin system

The n-channel accumulation layer FET was fabricated on a Si (100) wafer doped with $3\text{x}10^{17}$ P/cm^3 Details of the device and processing sequence have been previously described [12] The transistor was built at a voltage node of the half wavelength stripline resonator A compensating p-type implant was used to define a channel of length 1000μm and width 100μm, and four voltage probes were included along

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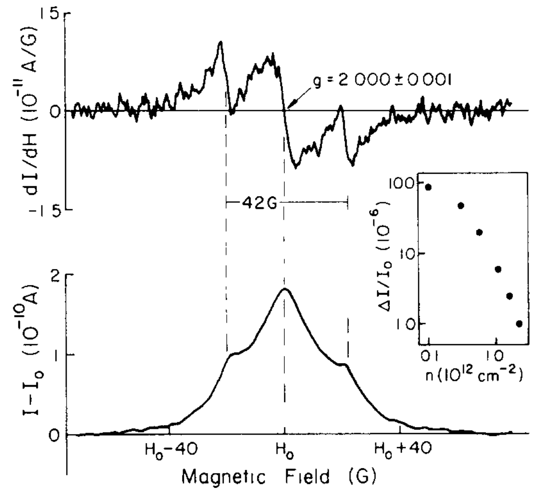

FIG. 1. (a) Derivative of the current and (b) the current itself as a function of magnetic field, $n=0.57\times10^{12}$ cm^{-2}, $I_0=10.0\mu A$, $H_0=3175G$ and microwave power=4dBm. Inset: Normalized peak SDT signal as a function of density, microwave power=10dBm. For all the data the field modulation is $H_{mod} = 2.5G_{pp}$.

the sides of the channel. The mobility was 3200 cm^2/Vsec, typical for a Si FET operating at 4K. The SDT experiment was performed with the transistor operating in the linear region of its current-voltage characteristic to ensure a uniform 2DEG density, n, from source to drain. The 2DEG density was measured via the Shubnikov-de Haas effect, and the results were in agreement with predictions from the device capacitance.

An expression for the change in current on resonance, $\Delta I/I_0$, provides a framework to discuss the experimental data.[13]

$$\frac{\Delta I}{I_0} = -\alpha\, s\, P_i^o P_c^o \left[\frac{R_n}{R_t} \right] \qquad (1)$$

I and I_0 are are the currents on and off resonance, P_i^o and P_c^o are the equilibrium spin polarizations of the impurity and conduction electrons, s is a saturation parameter, and R_n and R_t are the neutral impurity and total scattering rates. α is defined as $\alpha \equiv \langle \Sigma_S - \Sigma_T \rangle / \langle \Sigma_S + 3\Sigma_T \rangle$, where Σ_S and Σ_T are the singlet and triplet scattering cross sections. The angular brackets indicate a suitable average of the cross sections, as discussed below. The polarizations of the two spin systems are calculated by treating the impurity electrons as a non-interacting gas of spin 1/2 particles that obey Boltzmann statistics, while the conduction electrons are a degenerate Fermi gas. The saturation parameter $s \equiv [1-(1-s_i)(1-s_c)]$ is a measure of the degree to which these polarizations are destroyed by the microwave power coupled into the spin systems via the spin resonance. The impurity saturation parameter, s_i, is defined in terms of the impurity spin polarization, P_i, relative to P_i^o, by $s_i \equiv (1-P_i/P_i^o)$. A similar definition holds for the conduction electron saturation parameter, s_c. The SDT current is thus proportional to the difference between the singlet and triplet scattering cross sections, reduced by the relative strength of the neutral impurity to total scattering rates, and to the change in the product of the spin polarizations of the two spin species produced by the saturation of the resonance.

To measure the small change in device current due to spin dependent scattering a lock-in technique was used, with the transistor mounted in a modified x-band spectrometer. Fig. 1 shows both the derivative of the current and the current itself as a function of magnetic field. The observed line shape has a broad central feature with a g-value of 2.000 and two narrow components symmetrically displaced about the center. We interpret the split pair as due to the impurity electron spins. These electrons are bound to P donors (nuclear spin 1/2), known from bulk experiments to have a 42G hyperfine splitting.[14] Contributions from the conduction electron spins are contained in the central peak along with the exchange narrowed resonance of clusters of P donors.[15] Using samples with lower donor concentrations and appropriate relaxation rates, the experiment should reveal independently both the impurity and the conduction electron SDT spectra. For a given 2DEG density $\Delta I/I_0$ is independent of I_0, in agreement with the expectation that the SDT signal can be characterized as a conductance change.

A number of additional experiments were performed to support the assertion that the observed signal is due to spin dependent scattering. To check for spurious effects associated with microwave rectification in the contacts of our standard two probe (source-drain conductance) measurement, we did the four probe measurement shown in Fig. 2. The upper trace is dI/dH as a function of field, the lower trace is dV/dH which was measured using the voltage probes on the side of the channel. The fractional SDT signal is identical in both cases, ruling out effects related to contact rectification. Also, the contacts were doped with 2×10^{20} As/cm^3 (nuclear spin 3/2); spin resonance effects in the contacts would give either four hyperfine lines or a single exchange narrowed line, in contradiction with the observed lineshape.

We briefly consider another mechanism, based on the energy dependence of the mobility, which could result in a spin dependent device conductivity and show that is is not applicable to our experiment. When the electron system is spin-polarized there are different numbers of electrons in the spin up and spin down states so any energy dependent scattering mechanism would then result in a change in the sample conductance (σ). The fractional change in conduc-

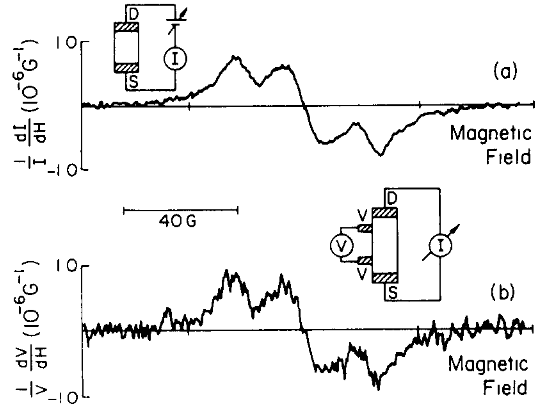

FIG. 2. (a) Normalized current signal as measured via the two probe setup. (b) Normalized voltage signal as measured via the four probe setup. For both traces $n=0.57\times10^{12}$ cm^{-2}, microwave power=10dBm and $H_{mod}=10G_{pp}$.

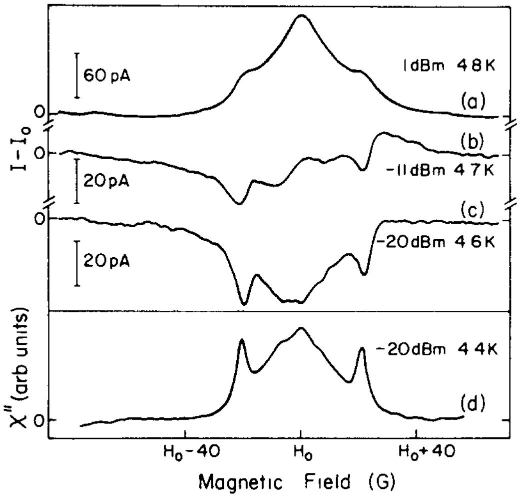

FIG. 3 (a-c) Current as a function of magnetic field for various microwave power levels, $n=0.57\times10^{12}$ cm^{-2}, $I_0=10.0\mu A$ and $H_{mod}=5G_{pp}$. (d) Absorption ESR spectrum, $H_{mod}=1.2G_{pp}$.

tance when the spin populations are fully equalized by spin resonance saturation, compared with the spin-polarized equilibrium state is given by

$$\frac{\Delta\sigma}{\sigma} = -\frac{1}{\mu}\left[\frac{g\beta H}{2}\right]^2 \left[\frac{1}{E_f}\left(\frac{d\mu}{dE}\right)+\frac{1}{2}\left(\frac{d^2\mu}{dE^2}\right)\right], \qquad (2)$$

where μ is the energy dependent mobility of the electrons, E_f their Fermi energy and $g\beta H$ the Zeeman splitting. The magnitude of this contribution may be evaluated from experimental data on the dependence of mobility on Fermi energy. Over most of the experimental range of E_f, the predicted signal is an order of magnitude or more smaller than the observed signal and it changes sign in the middle of the range of concentrations measured (the mobility goes through a maximum in this range), in clear disagreement with the data in the inset to Fig. 1.

Once the FET is mounted into the spectrometer both the conventional ESR signal and the current can be measured. Fig. 3d shows the standard ESR absorption spectrum of the sample. The lineshape is as expected[15] for bulk Si doped with 3×10^{17} P/cm^3, donor clusters contributing to the feature between the two hyperfine lines. The current signal was measured over five decades of microwave power (from +10dBm to –40dBm), representative spectra are shown in Fig. 3a–c. Note that SDT, which is observed in the high power spectrum (Fig. 3a), has a different line shape from the ESR spectrum (Fig. 3d). As the power decreases there appears a fascinating new signal of the opposite sign and with a different lineshape!

We attribute the low power (≤–20dBm) signal to bolometric detection of the bulk phosphorus ESR. In the absence of magnetic resonance, measurement of the FET current shows a positive but saturating non-linear dependence on microwave power which we interpret as a change of channel conductance produced by heating of the sample by microwave dissipation (P_μ) in the resonator strip. At higher powers, the slope of dI/dP_μ decreases and then changes sign for powers above 10 dBm. At low power for an undercoupled resonator, the absorption of power by the bulk ESR results in a reduction of the total power dissipated in the sample plus strip, and hence a reduced device current as observed. The magnitude of the signal observed is consistent with the calculated ESR dissipation together with the bolometric sensitivity determined from the $I(P_\mu)$ characteristic.[13] The correct sign, lineshape (compare Fig. 3c and 3d) and magnitude support the identification of the low power current signal as bolometric detection of bulk ESR.

It is impossible, however, to interpret the high power SDT signal (≥ -8dBm) in terms of bolometric response either to the bulk spins or to the spins in the channel region in interaction with the channel electrons. For the bulk spins, both the sign of the signal is wrong (the power here is well below the power at which the bolometric sensitivity reverses sign) and the lineshape does not correspond to the conventional ESR (or low power current detected) signal. To estimate the bolometric sensitivity to spins in the channel region we combine the values of the electron-phonon relaxation rate[11,16] (we use 4×10^{-10} s at 4 K) with the measured temperature coefficient of conductance of 3×10^{-8} A/K. The calculated bolometric signal[13] is three orders of magnitude smaller than the observed signal at 1 dBm. This estimate is conservative because heating, as evidenced from the $I(P_\mu)$ characteristic, will reduce thermal impedances to lower values. Further, in a sample in which the study was carried to higher powers, the SDT signal was observed to remain of the same sign in the highest power regime while the slope of the bolometric response dI/dP_μ reversed. Both the observed magnitude and the absence of a sign reversal of the signal dictate against the interpretation of the SDT signal as bolometrically detected.

The expression for the SDT signal in Eq. 1 indicates that complete saturation of either the impurity or conduction electron spins (s=1) would result in a signal whose strength becomes independent of power at high power. In the range from 7 dBm to 13 dBm, $\Delta I/I_0$ remained approximately constant, suggesting saturation of the resonance. However, this is the power regime in which we believe heating is an issue so that both a reduction of equilibrium polarization and a shortening of relaxation times at the higher sample temperature may also contribute to the saturation of the signal with microwave power. A study of the power dependence at low power was not possible because of interference from the bolometrically detected bulk ESR signal below –10dBm.

Measurements of the device current at 2.3K yielded results similar to Fig. 3a–c. The SDT signal was approximately 40% larger, less than the predicted change of a factor of two. The reduced temperature dependence may relate to the freezing of antiferromagnetically coupled clusters into states of low J, as discussed by New and Castner.[15] It may also reflect microwave heating of the system at the higher powers. The low power ESR signal corrected for the bolometer sensitivity, was roughly a factor of two larger at the lower temperature, which is the anticipated Curie-law behavior.

Experiments were performed with the DC magnetic field both perpendicular and parallel to the plane of the 2DEG. Only small changes in the SDT lineshape and magnitude were observed. Orientation dependence due to Landau level structure would not be expected because we are in the low field limit with unresolved Landau levels.

A free parameter in our experiment is the Fermi energy (E_f) of the conduction electrons. The peak value of the spin dependent current, normalized with respect to I_0, is plotted as a function of the 2DEG density in the inset to Fig. 1. As the density is increased by a factor of 20, the signal decreases by about two orders of magnitude Considering only the conduction electron polarization term in Eq 1, we expect $\Delta I/I_0$ to scale as $1/E_f$, or inversely with the 2DEG density, explaining a major portion of the density dependence Additional sources of density dependence include energy dependence of the singlet and triplet scattering cross sections[17] and of spin relaxation times

The SDT signal is positive over the entire range of densities studied, which implies, using Eq 1, that $\alpha < 0$ This experimental result is in striking disagreement with the theories of neutral impurity scattering[3,17] in three dimensions, which predict a positive value for α in the low energy limit We are aware of no calculations of the relevant scattering cross sections for the two dimensional (2D) case of interest to us In Eq 1, the dimensionality of the problem enters the definition of the averaging in the parameter α, as well as via the cross sections The angular brackets indicate a weighted average over all angles as appropriate in determining a momentum scattering rate, an additional average over z, the coordinate of the neutral donor perpendicular to the semiconductor/oxide interface, must be included in 2D The z dependence of the scattering cross section includes effects of the spatial extent of the 2DEG wave function and the range of the effective scattering potential The distribution[18] of neutral impurities as a function of depth sets the lower limit on the z integration The comparable magnitude of these three length scales precludes meaningful adaptation of the 2D cross sections from their known 3D versions[17] in order to predict the 2D experimental results. Only a real calculation of the 2D cross sections will permit a quantitative comparison of theory with experiment

We have made direct measurements of neutral impurity scattering in Si This spin dependent transport signal was characterized as a function of microwave power, temperature, orientation of the DC magnetic field, and the Fermi energy of the conduction electrons We hope these results will stimulate theoretical analysis of the the two dimensional scattering problem

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REFERENCES

1 G L Pearson and J Bardeen, Phys Rev **75**, 865 (1949)

2 C Erginsoy, Phys Rev **79**, 1013 (1950)

3 For a review see B K Ridley, *Quantum Processes in Semiconductors 2nd ed*, (Clarendon Press, Oxford, 1988)

4 P. Norton, T Braggins and H Levinstein, Phys Rev B **12**, 5632 (1973)

5 R. Baron, M H Young and T. C. McGill, in *Proc of 13th Int Conf on Physics of Semiconductors 1976* (North Holland Pub Co , New York 1976), p 1158

6 A Honig, Phys. Rev Lett **17**, 186 (1966)

7 J Schmidt and I Solomon, C R Acad Sc. Paris **263**, 169 (1966)

8 R Maxwell and A Honig, Phys Rev Lett **17**, 188 (1966)

9 D D Thorton and A Honig, Phys Rev Lett **30**, 909 (1973)

10 D Stein, K v Klitzing and G Weimann, Phys Rev Lett **51**, 130 (1983)

11 F Neppl, J Kotthaus and J Koch, Phys Rev B **19**, 5240 (1979)

12 R N Ghosh and R H Silsbee, Cryogenics **30**, 1069 (1990)

13 R N Ghosh, Ph D thesis, Cornell University, 1991 (unpublished), R N Ghosh and R H Silsbee (to be published)

14 G Feher, Phys. Rev **114**, 1219 (1959)

15 D New and T G. Castner, Phys Rev. B **29**, 2077 (1984)

16 C C Dean and M Pepper, J Phys C **17**, 5663 (1984)

17 P G Burke and H. M. Schey, Phys Rev **126**, 163 (1962)

18 Only donors in the region where 4meV < E_c - E_f are neutral because the downward bending of the conduction band edge (E_c) at the interface populates the doubly occupied P^- state Binding energy of 4meV is obtained from P Norton, J Appl Phys **47**, 308 (1976).