Resistively detected microwave absorption by planar spin oscillators

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Abstract. We report on a novel class of RF spintronics devices directed towards making nanoscale microwave sources. Microwave emission is produced by a process of spin resonance that occurs in hybrid semiconductor-ferromagnetic nanostructures when a two-dimensional electron gas is subjected to both a magnetic field gradient and a constant magnetic field applied at right angles of each other. Current injection activates electron spin oscillations in the magnetic field gradient, whilst conversely, driving the spin dynamics with a microwave field modifies the channelling resistance perpendicular to the magnetic field gradient. We have irradiated GaAs/AlGaAs/Dy nanowires and observed resistance peaks induced by the microwave field. We have analyzed their dependence in the 50-110GHz and the 6T-15T range to extract relevant spin parameters. The absorption of microwave by spin oscillators is compared to the ferromagnetic resonance of Dysprosium.

1. Introduction

Electron spin resonance (ESR) in the conduction band of semiconductor crystals provides accurate measurements of the Landé g-factor [1,2] and the zero field spin-orbit splitting [3] and allows a direct comparison of these parameters with band structure calculations. The advent of modulation doping of semiconductor quantum well structures has enhanced the resolution of ESR spectra by allowing spectroscopy at low temperature and by avoiding the line broadening due to bulk doping. Since the early work of Weisbuch et al. [1] the saturation of ESR has been detected by the degree of circular polarization in the photoluminescence signal. The electrical detection of ESR has proved more difficult to observe. This is because, in addition to spin polarization, the physical system must exhibit different spin up and spin down conductivities for a change is resistivity to be observed when ESR is saturated. Resistively detected ESR has therefore required a discrete density of state such as the one obtained when the Fermi level lies between spin split Landau levels [3] or in the fractional quantum Hall regime [4]. At low magnetic field microwave photoconductivity has shown coupling to plasmonic resonances [5] and to zero resistance states [6].

In this paper we investigate the microwave photoconductivity of a two dimensional electron gas (2DEG) subjected to a gradient of magnetic field perpendicular to the plane and to a large in plane magnetic field - see Fig.1. The magnetic field gradient has the effect of binding electrons to an oscillatory motion centered at the point where the magnetic field gradient vanishes. These
oscillations have the effect of subjecting the electron spin to a periodic torque oscillating at the frequency of the electron oscillator. At the same time, the electron spin describes a precession motion about the in-plane component of the magnetic field. Consequently magnetic resonance occurs when the frequency of the spin oscillator matches the Larmor frequency. It follows the very interesting and novel situation where the orbital and the spin degree of freedom of the spin oscillator become interdependent of each other. For example, an electron that skips between two oscillator states as a result of momentum scattering will see a time dependent magnetic field oscillating at a different frequency forcing a change in spin dynamics. Conversely, a external microwave field will drive spin oscillations hence perturbing orbital motion and modifying the electrical conductivity. Microwave absorption will therefore perturb the conductivity tensor at low magnetic field i.e. in the absence of Landau quantization. This we measure below. It is also significant that spin oscillators correspond to open orbits which contribute the largest drift to the conductivity tensor among all electrons within the Fermi disk [7,8,9].

Figure 1. Planar spin oscillator device consisting of a magnetically modulated 2DEG.  
Figure 2. Experimental setup for microwave absorption by spin oscillators.

The spin oscillator device is described in Figure 1. The stray magnetic field emanating from the ferromagnetic gate threads the two-dimensional electron gas with both a magnetic field component $B_1$ varying linearly away from the centre of the channel and a magnetic field component $B_0$ which is constant. The magnetic field gradient introduces two novel physical scales associated with the amplitude of electron oscillations $l_b = 2\sqrt{\hbar k_F/(eb)}$ and the range of oscillator frequencies $0 - \omega_c$ where $\omega_c = \sqrt{\hbar k_F eb/m^*}$. We have used $k_F$ as the Fermi wavevector of the 2D electrons, $b = dB_1/dz$ as the gradient of magnetic field, $m^*$ as the electron effective mass, $\hbar$ and $e$ are the reduced Planck’s constant and the electron charge respectively. $\omega_c$ represents the maximum frequency of an orbit traveling parallel to the centre of the channel. This frequency was also shown to indicate the maximum coupling of the distribution of spin oscillators to the electromagnetic field [10]. Unlike the cyclotron frequency which is independent of the electron concentration, $\omega_c$ may be controlled by a gate voltage. This is a result of interest for applications concerned with tunable microwave absorption/emission [11,12].

2. Experimental
A small wire section was etched out of a GaAs/AlGaAs HEMT structure. The two-dimensional electron gas was formed 35nm beneath the surface and had a nominal electron density of $n_s = 4.31 \times 10^{11} \text{cm}^{-2}$ in the dark and a mobility $\mu = 4.63 \times 10^5 \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$. Magnetic stripes of various materials (nickel, iron and dysprosium) were fabricated at the centre of the wire to give the magnetic field profile of Fig.1. The devices were ungated but most experiments were performed by irradiating the device from the back as shown in Fig.2 to avoid screening by the magnetic stripe. Sample 1 and 2 had dysprosium stripes 160nm and 90nm thick respectively. The
samples were cooled at 1.5K and mounted in such a way as to align the external magnetic field ($B_{ext}$) in the plane of the 2DEG and parallel to $B_0$. Alignment was correct within a few degrees of angle. The residual perpendicular magnetic field as detected by a linear background in the Hall voltage was less than 0.1T at 15T and much less than $B_1$. $B_{ext}$ acts as the Larmor magnetic field which we ramp as in conventional ESR. $B_{ext}$ also serves to saturate the stripe magnetization along its short axis. The sample resistance was obtained using quasi-dc measurements with a lock-in amplifier.

The microwave beam output by the rectangular waveguide was reflected by a metallic mirror before reaching the sample. The polarization on the sample was therefore random. Indeed rotating the waveguide showed little anisotropy. The power output by the carcinotron was varied continuously using an attenuator between 0 and 20mW. The frequency was varied between 50GHz and 120GHz. The spectral distribution of the emitted power showed fluctuations over the frequency range which is the reason why resonant measurements were taken by sweeping the magnetic field at constant values of the microwave frequency. Microwave heating was found to start attenuating Shubnikov-de Haas oscillations above -5dBm. Our results were obtained with a power level of -10dBm.

3. Results

Figure 3. Magnetoresistance of sample 1 and second derivative showing a frequency dependent peak at high magnetic field.

Figure 4. Magnetic field dependence of the peak as a function of the microwave frequency.

Fig.3 shows the magnetoresistance - $B_{ext}$ in the plane - of sample 1 for three values of the microwave frequency. We observe a resistance peak above 8T that moves to higher frequency as the microwave frequency increases. The peak position is obtained from the second derivative curve and plotted in Fig.4 as a function of the microwave frequency. We fitted the slope by equating the Zeeman energy to the photon energy and find the modulus of the Landé g-factor to be 0.88. Extrapolating the linear trend at zero frequency gives an offset magnetic field of 4.9T. This is partly explained by the in-plane stray magnetic field $B_0$ which we evaluate to be of the order of 1T when the magnetization is saturated and uniform.

Fig.5 shows the magnetoresistance of sample 2 measured in the same conditions as above, the only difference being the thinner Dy stripe. The longitudinal resistance now shows a qualitatively
different structure below 5T but no high field peak. Its position has a markedly different frequency dependence plotted in Fig. 6. We find the Landé g-factor of this resonance to be 1.9 and observe that the resonant field extrapolates to zero at zero frequency.

**Figure 5.** Low field magnetoresistance of sample 2 sensing the ferromagnetic resonance of Dy across the 2DEG.

**Figure 6.** Magnetic field dependence of the ferromagnetic resonance peak as a function of the microwave frequency.

**4. Conclusion**

We interpret the resonance observed in sample 1 as the absorption of microwaves by spin oscillators based on the value observed for the electron g-factor which is close to that expected for electrons in GaAs. In addition a magnetic field offset is present that is consistent with the existence of a strong in-plane stray magnetic fields at the site of the 2DEG. The resonance observed in sample 2 by contrast is the ferromagnetic resonance of dysprosium detected across the 2DEG [13]. We therefore believe that we have observed ESR by planar spin oscillators. These experiments emphasize the need to further elucidate the effect of stripe dimensions and to better control its magnetic properties.

**References**

[1] Weisbuch C, Hermann C 1977 *Phys. Rev. B* **15** 380
[2] Seck M, Potemski M, Wyder P 1997 *Phys. Rev. B* **56** 7422
[3] Stein D, von Klitzing K, Weimann G 1983 *Phys. Rev. Lett.* **51** 1983
[4] Kukushkin IV, Smet JH, von Klitzing K, Wegscheider W 2002 *Nature* **415** 409
[5] Kukushkin IV et al. 2003 *Phys. Rev. Lett.* **90** 156801
[6] Smet JH et al. 2005 *Phys. Rev. Lett.* **95** 116804
[7] Lawton D, Nogaret A, Makarenko MV, Kibis OV, Bending SJ, Henini M 2002 *Physica E* **13** 699
[8] Hara M, Endo A, Katsumoto S, Iye Y 2004 *Phys. Rev. B* **69** 153304
[9] Nogaret A, Bending SJ, Henini M 2000 *Phys. Rev. Lett.* **84** 2231
[10] Nogaret A 2005 *Phys. Rev. Lett.* **94** 147207
[11] Kiselev SL, Sankey JC, Krivorotov LN, Emley NC, Schoelkopf RJ, Buhrman RA, Ralph DC 2003 *Nature* **425** 380
[12] Kaka S, Pufall MR, Rippard WH, Silva TJ, Russek SE, Katine JA 2005 *Nature* **437** 389
[13] Rossol FC, Jones RV 1966 *J. Appl. Phys.* **37** 1227