Double spin resonance in a spatially periodic magnetic field with zero average


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We report on the electrical detection of spin resonance in a two-dimensional electron system modulated by a periodic magnetic field with zero average. Spin degeneracy is lifted by a large magnetic field applied in the plane while the system is irradiated with microwaves. Without magnetic modulation, the resistance does not detect spin resonance. However an absorption peak develops as the magnetic modulation is switched on. The frequency and temperature dependences of the peak yield the Zeeman energy of electrons in the GaAs/AlGaAs quantum well. We interpret the absorption peak as the result of competition between two spin-flip transitions: one activated by snake orbits oscillating at the boundary between positive and negative magnetic field domains, the other by microwaves. When both transitions are simultaneously resonant, the system forms a dark state which blocks spin flips and freezes snake orbit channelling. The coherent suppression of snake orbit channelling explains the experimental features of the observed resonance.

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Abstract – We report on the electrical detection of spin resonance in a two-dimensional electron system modulated by a periodic magnetic field with zero average. Spin degeneracy is lifted by a large magnetic field applied in the plane while the system is irradiated with microwaves. Without magnetic modulation, the resistance does not detect spin resonance. However an absorption peak develops as the magnetic modulation is switched on. The frequency and temperature dependences of the peak yield the Zeeman energy of electrons in the GaAs/AlGaAs quantum well. We interpret the absorption peak as the result of competition between two spin-flip transitions: one activated by snake orbits oscillating at the boundary between positive and negative magnetic field domains, the other by microwaves. When both transitions are simultaneously resonant, the system forms a dark state which blocks spin flips and freezes snake orbit channeling. The coherent suppression of snake orbit channeling explains the experimental features of the observed resonance.

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Introduction. – The rapid emergence of spintronics is stimulated by the benefits of addressing individual spins in devices \[1,2\]. One way to control the spin is by shifting electrons between regions of opposite magnetic field. This can be done either by means of electrostatic gates \[3\] or by using the sign reversal of the Lorentz force to produce "snake" orbits that meander between positive and negative magnetic field domains \[4,5\]. Spatially varying magnetic fields which reverse sign are obtained by patterning ferromagnets at the surface of a two-dimensional electron gas (2DEG). The undulation of snake trajectories in the canted magnetic field subjects the electron spin to a time dependent magnetic field that oscillates at microwave frequencies \(\sim 100\,\text{GHz}\). Snake-induced Electron Spin Resonance (SESRR) occurs when the oscillation frequency of a snake orbit equals \(g\mu_BB_0/\hbar\) \[6\]. A feature that has received little attention is the huge amplitude of the alternating magnetic field, typically \(\sim 0.1\,\text{T}\), which makes the Rabi frequency larger than the spin relaxation rate and opens the possibility of coherently manipulating the electron spin.

Here, we investigate the electrical conductivity of lateral magnetic superlattices under microwave irradiation to study the interplay between SESRR and Microwave-induced Electron Spin Resonance (MESR). The grating applies a spatially varying magnetic field that deflects electron trajectories in the two-dimensional electron gas (2DEG). An external magnetic field is applied in the plane to induce spin precession. We report an absorption peak in the resistance of the magnetically modulated 2DEG when MESR crosses resonance. Such peak is \textit{a priori} unexpected because, the density of states being two-dimensional, spin-up and spin-down channels have equal conductivities.
In which case, spin flips would leave the resistance unchanged. We verify that this assumption is true in the unmodulated 2DEG. By switching the magnetic modulation off we have demonstrated the suppression of the resistance peak. Our experiment differs from earlier experiments on resistively detected spin resonance in that here the 2DEG is ballistic and Landau quantization is not used to differentiate spin-up and spin-down conductivities [7–9]. We measure the frequency dependence of the absorption peak and obtain the Landé g-factor of electrons in the GaAs/AlGaAs heterojunction. We also find that the thermal activation energy of the absorption peak corresponds to the Zeeman energy in the GaAs quantum well. To explain the change in resistance caused by spin flips, we argue that inhomogeneous magnetic fields introduce electron states that couple orbital and spin motion. One example of these states are snake orbits whose spin phase depends on the electron path in the magnetic potential. Here, we show that the MESR transition freezes snake orbit channelling by blocking spin flips. We compute the change in resistance induced by spin flips. We measure the frequency dependence of the unmodulated 2DEG. By switching the magnetic field \( \Delta \frac{\rho}{\rho_0} \approx 1800\% \) [13].

Experiments were conducted in an external magnetic field \( B_o \) applied in the plane of the 2DEG. \( B_o \) was used to magnetize the cobalt fingers. We were able to turn the magnetic potential ON or OFF by applying \( B_o \) along the short or the long axis of the stripes. \( B_o \) was also used as the Larmor field giving the frequency of spin precession \( \omega_0 = g_y \mu_B B_0 / h \). \( B_o \) was carefully aligned with the 2DEG to minimize any residual perpendicular component. The sample was first coarsely aligned on the probe to within 1°. The in-plane alignment was then finely tuned by adjusting the height of the sample relative to the center of the superconducting magnet. The Hall resistance minimum was found within ±2 cm of the centre of the field. Samples were mounted vertically at the end of an overmoded circular waveguide. A copper mirror was used to redirect microwaves onto the sample surface as shown in fig. 1(a). The resistance was measured using low frequency lock in detection, the current bias (500 nA) was along the stripes (\( x \)-direction).

The low field magnetoresistance \( \rho_{xx} \) and the Hall resistance \( \rho_{xy} \) are now used to obtain the amplitude of the magnetic modulation \( B_1 \). The dependence of \( \rho_{xx} \) on \( B_o \parallel y \) (full lines) and \( B_o \parallel x \) (dashed lines) is shown in fig. 2(a).

\[ \Delta \rho_{xx}/\rho_0 = 25\% \] develops between 0 and ±0.3 T. This range of magnetic fields corresponds to the reversal of the magnetization in the Co grating (fig. 2(b)). \( \Delta \rho_{xx}/\rho_0 \) hence results from the reduction of the electron mean free path by the rising magnetic modulation. The sinusoidal
Doublespin resonance in a spatially periodic magnetic field

Fig. 2: (Colour on-line) (a) Magnetoresistance of the cobalt superlattice measured with $B_a \parallel y$ (full lines) and $B_a \parallel x$ (dotted lines); (b) magnetization curve of the cobalt grating measured by Hall magnetometry ($B_a \parallel y$); (c) frequency dependence of the ESAR peak; (d) microwave-induced resistance $\Delta \rho_{xx}^{\mu W}$ mapped as a function of $\omega_r$ and $B_a$ ($B_a \parallel y$).

magnetic field $B_{1,z}(y)$ decreases the number of ballistic conduction channels [12] by introducing magnetic potential barriers [11,14] which reflect electrons with transverse momentum $k_y < k_b = eB_1a/\hbar$. Such modes are confined to one period of the magnetic superlattice. Modes with momentum $k_y > k_b$ extend over the barriers, over approximately 30 lattice periods, a distance limited by the mean free path. A simple calculation shows that the magnetic potential decreases the number of extended modes by $\Delta N/N_0 = (1 - k_b/k_F)^2 - 1$. As a result, the Drude resistivity $\rho_0 = (\hbar/e^2)N_0^{-1}$ increases by $\Delta \rho_{xx}/\rho_0 = -\Delta N/N_0$. Given that $\Delta \rho_{xx}/\rho_0 = 25\%$, we estimate the amplitude of the magnetic modulation to be $\tilde{B}_1 = 0.139 T$. A calculation of the field emanating from the grating [10,11] gives $\tilde{B}_1 = \mu_0 M_y/(2\pi) \sin(Qd/2) \sinh(Qw/2)e^{-Q(z_0+w/2)}$. Using the tabulated saturation magnetization of cobalt $\mu_0 M_y = 1.82 T$ and the device dimensions in fig. 1(a), we find $\tilde{B}_1 = 0.141 T$, in agreement with the experimental value. When $B_a \parallel x$, the V-shaped magnetoresistance vanishes, not surprisingly, because $M_y = 0$ gives $\tilde{B}_1 = 0$.

We now turn to the microwave-induced structure in fig. 2(a). We label the resistance peak at 10.3 T ESAR (Electron Spin Anti-Resonance) because conventional ESR is not detected in the ballistic regime of the 2DEG. The conductivities of spin-up and spin-down electrons being the same, spin flips have no net effect on the overall conductivity. We verify this by magnetizing the stripes along $x$ to suppress the magnetic modulation (dotted lines) and show that the resistance has no absorption peak at any value of the microwave power. The magnetic potential must therefore introduce electron states that couple the spin to the orbital dynamics enabling the electrical detection of spin resonance. At low magnetic field, the 2DEG detects the ferromagnetic resonance (FMR) of the grating giving the dip seen between 2.6 T and 3.5 T (full lines).

The ESAR and FMR are identified by their frequency dependence in figs. 2(c) and (d). Panel (d) maps the ESAR and FMR amplitude $|\Delta \rho_{xx}^{\mu W}|$ obtained by subtracting the background resistance measured at zero microwave power. The frequency dependence of the ESAR peak position was interpolated with a least square method weighting in the peak amplitudes (dashed line) which we fitted using the frequency dependence of the Zeeman gap $\omega_r = |g||\mu_B|B_a + B_N)/\hbar$. $\omega_r$ is the angular frequency of microwaves, $\mu_B$ is the Bohr magneton and $g$ is the Landé $g$-factor in the quantum well. The fit gives $|g|| = 0.43 \pm 0.04$ and $B_N = 4.53 T \pm 0.3 T$. The Landé factor obtained from a fit of FMR is $g^* = 1.8 \pm 0.04$. The accepted value for cobalt is $g^* = 1.83$ [15].

The Landé $g$-factor in the quantum well can also be obtained from the temperature dependence of the ESAR peak—see fig. 3(b). The amplitude of the ESAR peak $\Delta \rho_{xx}^{\mu W}(T)$ is assumed to be proportional to the fraction of redistributed spins $(N_\uparrow - N_\downarrow)/N_\uparrow = 1 - \exp(-\Delta/k_BT)$ where $\Delta$ is the Zeeman gap. Hence, the peak amplitude

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follows the thermal activation law \( \Delta \rho_{xx}^W(T) = \Delta \rho_{xx}^W(0) \left[ 1 - \exp\left( -\Delta / (k_B T) \right) \right] \). The ratio \( \Delta \rho_{xx}^W (1.7 K) / \Delta \rho_{xx}^W (0) = 0.89 \) was obtained by requiring the alignment of the data points in Fig. 3(a). The slope gave the activation energy: \( \Delta = 0.342 \text{ meV} \). Writing \( \Delta = |g| \mu_B (B_a + B_N) \), \( B_a = 10.3 \text{ T} \) and \( B_N = 4.53 \text{ T} \), the fit of the temperature dependence gives \( |g| = 0.40 \). Within experimental error, this is the \( g \)-factor obtained from the frequency dependence. The theoretical value for a 15 nm wide GaAs quantum well is \( |g| = -0.42 \).

The dependence of the ESAR peak on microwave power is obtained in Fig. 4. \( B_N \) is obtained from the shift of the peak position relative to the bare resonant field given by \( h \omega_r / (g \mu_B) \). Panel (c) shows that \( B_N \) decreases from 5.6 T at -12 dB to 4.9 T at 0 dB and that it extrapolates to 5.7 ± 0.2 T at zero microwave power. This \( a \) \( priori \) suggests that the nuclear spin system is polarized close to saturation [17] at zero microwave power. To determine whether SESR might dynamically polarize nuclear spins, we study the dependence of \( B_N \) on the intensity of the current drive. This study was done in a dysprosium superlattice and is shown in Fig. 3(c). The ESAR peak shifts to lower field when the current increases which shows that \( B_N \) increases from 0 T at 0 \( \mu \text{A} \) to 0.45 T at 1.5 \( \mu \text{A} \). In the meantime the position of the MFR peak is constant which eliminates heating as the source of the drift. The increase in \( B_N \) with increasing current suggests that the current dynamically polarizes nuclei possibly through the SESR mechanism. By contrast, increasing the microwave power reduces \( B_N \). The joint effect of MESR and SESR is to decrease the nuclear spin polarization. One may also assume that the hysteresis of the ESAR peak is due to the long relaxation time of nuclei after these have been dynamically polarized when the electron system crosses the antiresonance.

**Snake oscillators in a sinusoidal magnetic field.**

We develop a semiclassical theory of snake orbits in a sinusoidal magnetic field to calculate both the angular frequency of snake oscillations \( \omega_1 \) and the Rabi frequency of the SESR transition \( \Omega_1 \). The inhomogeneous magnetic field deflects the electron velocity at a rate \( (v_x, v_y, v_z) = \omega_c(y)(-v_y, v_x, 0) \) where \( \omega_c = \gamma \sqrt{B_{1z} \gamma} / m^* \) is the local cyclotron frequency in the magnetic field \( B_{1z}(y) = B_{1z} \sin(Qy) \). \( (\gamma = 0.141 \text{ T}) \). \( v_x(y) \) is easily obtained by integration once the initial condition \( v_x(y=0) = v_F \cos \theta \) is specified. \( \theta \) is the angle at which the trajectory crosses the line of zero magnetic field. \( v_y(y) \) is obtained by stating that the electron velocity is the Fermi velocity: \( v_x^2 + v_y^2 = v_F^2 \). One arrives at the transverse equation of motion of the snake oscillator:

\[
(\gamma \gamma')^2 [1 - \gamma^2 Y^2] [\cos^2(\theta/2) - Y^2] [Y^2 + \sin^2(\theta/2)] = 0.
\]  

The position \( Y \) is dimensionless and relates to the real space coordinate \( y \) through

\[
Y = \sin(Qy/2) / \gamma, \tag{2}
\]

where \( \gamma = Ql \) (2.7) and \( l = \sqrt{\hbar k_F / (e b)} \) (172 nm) is the largest possible amplitude of an oscillator [6] in gradient of magnetic field \( b \). In the case of a sinuosidal magnetic modulation \( b = Q B_1 \) (2.2 T/\( \mu \text{m} \)). Equation (1) describes an anharmonic oscillator centered at \( y = 0 \) and oscillating with amplitude \( \gamma = \cos(\theta/2) \). The amplitude of oscillations in real space \( \gamma \) depends on the strength of the magnetic confinement through parameter \( \gamma \). If \( \gamma < 1 \) (strong magnetic confinement), eq. (1) has real solutions because its right-hand side is always positive. The maximum possible value for \( \gamma \) is 1 as a result all electrons on the Fermi surface are confined to a bundle of snake orbits of width \( \gamma_{\text{max}} = (2Q)^{-1} \) arsec \( \gamma \). If \( \gamma > 1 \) (weak magnetic confinement), there exists a critical angle \( \theta_c \) at which a snake orbit touches the boundary of the superlattice period (\( \gamma = a/2 \)) and becomes an extended orbit.
dispersion curve \( \omega \) and MESR transition \( (\omega, \Omega_r) \) across the Zeeman gap. There are \( N \) photons in mode \( \omega_r \), the longitudinal and transverse spin relaxation rates are \( \gamma_L \) and \( \gamma_T \). (d) Fit of the ESAR line of the oscillator amplitude; (c) SESR driven transition \( (\omega_1, \Omega_1) \) and MESR transition \( (\omega_r, \Omega_r) \) through the relation \( \omega = 110 \text{GHz} \) (squares) with eq. (13) (full lines).

\[
\ddot{y} = a/2 \text{ in eq. (2) gives } \dot{Y} = -\gamma^{-1}, \text{ hence } \theta_c = 2 \arccos(\gamma^{-1}). \text{ With } \gamma = 2.7, \text{ our superlattice falls into this second category with a critical angle } \theta_c = 136^\circ. \text{ Trajectories with angle } \theta \text{ comprised between } 180^\circ \text{ and } 136^\circ \text{ are snake orbits. Those between } 136^\circ \text{ and } 0 \text{ are extended orbits.}
\]

The period of the oscillator is calculated by integrating eq. (1). The angular frequency of snake oscillations is \( \omega_1 (\ddot{y}) = \omega_1 / [4F(\pi/2, \ddot{y})] \) where

\[
F(\pi/2, \ddot{y}) = \int_0^{\pi/2} \frac{d\alpha}{\sqrt{1 - \dot{Y}^2 [1 + \gamma^2 (1 - \dot{Y}^2)] \sin^2 \alpha}}. \tag{3}
\]

\( \omega_1 = \sqrt{\hbar k_F eB/m^*} \) is the maximum angular frequency of snake oscillators and \( \dot{Y} = \sin(Q\ddot{y}/2)/\gamma \). We parametrize \( \omega_1 \) with \( \ddot{y} \) rather than \( \theta \) to facilitate the discussion given that \( \ddot{y} \) varies between 0 and \( a/2 \). \( \ddot{y} \) is related to \( \theta \) through the relation \( \gamma \cos(\theta/2) = \sin(\dot{y}(\ddot{y}/2)). \) The dispersion curve \( \omega_1 (\ddot{y}) \) is plotted in fig. 5(a). Snake orbits of amplitude \( \ddot{y} \sim 0 \) oscillate at the maximum frequency \( \omega_1/(2\pi) = 150 \text{GHz} \) whereas those of maximum amplitude \( \ddot{y} \sim a/2 \) have zero frequency. The Rabi frequency of SESR is \( \Omega_L (\ddot{y}) = |g| |\mu_B B_{1z}(\ddot{y})|/\hbar \) and is plotted in fig. 5(b). \( \Omega_L (\ddot{y}) \) has a maximum \( \Omega_L/(2\pi) = 0.81 \text{GHz} \) at \( \ddot{y} = a/4 \).

The SESR picture is summarized in fig. 1(c). Resonance is reached at \( \omega_1 = \omega_0 \). When this happens, the wiggling motion of a snake orbit is accompanied by spin flips. The rate of spin flips (Rabi frequency) is about 100 times slower than the frequency of the snake oscillator. The standard textbook picture of MESR requires the three following modifications to properly describe SESR: the alternating magnetic field of SESR is linearly polarized instead of being circularly polarized, it is periodic but not sinusoidal [6], spin flips are propelled by the electric bias not by photons as in MESR. In MESR, Rabi oscillations involve the absorption and re-emission of the same photon. In SESR, a spin gains energy by absorbing a small fraction of the kinetic energy of an electron accelerated in the d.c. electric field. This energy is then given back to the electron when the spin returns to its ground state in the second half of the cycle.

**Double spin resonance.** The Zeeman gap is bridged by two transitions which couple states \( | \downarrow, N \rangle, | \downarrow, N + 1 \rangle \) and \( | \uparrow, N \rangle \) —see fig. 5(c). Here \( N \) is the number of microwave photons in the sample cavity at frequency \( \omega_r \). The SESR transition \( (\omega_1, \Omega_1) \) conserves the photon number whereas the MESR transition \( (\omega_r, \Omega_r) \) does not. The SESR transition remains resonant because the oscillator spectrum is continuous. There is always one oscillator mode matching the Larmor frequency so that the resonant condition \( \omega_1 = \omega_0 \) is satisfied. When the microwave transition crosses resonance at \( \omega_r = \omega_0 \), the initial states hybridize to form a dark state: \( |d\rangle = \frac{\Omega_r}{\sqrt{\Omega_r^2 + \delta^2}} | \downarrow, N + 1 \rangle - \frac{\Omega_r}{\sqrt{\Omega_r^2 + \delta^2}} | \downarrow, N \rangle \). The system decays into this state with no way out since \( |d\rangle \) has no component on \( | \uparrow, N \rangle \). The probability of the dark state is the expectation value of the density matrix:

\[
P_{\text{dark}} = \langle d | \hat{\rho} | d \rangle. \tag{4}
\]

One obtains the density matrix given the Hamiltonian of the unperturbed three-level system \( H_0 = \hbar \omega_0 | \downarrow, N \rangle \), and the interaction Hamiltonian arising from both transitions:

\[
H_{\text{int}} = \frac{\hbar}{2} \begin{pmatrix} 0 & 0 & \Omega_r \\ 0 & 2\delta & \Omega_1 \\ \Omega_r & \Omega_1 & -2\delta \end{pmatrix}, \tag{5}
\]

where \( \delta = \omega_0 - \omega_r \) is the detuning of microwaves from resonance. The density matrix obeys the following rate equations [18]:

\[
\dot{\rho}_{11} = i \frac{\Omega_r}{2} (\rho_{13} - \rho_{12}) + \rho_{33} \frac{\gamma_T}{2}, \tag{6}
\]

\[
\dot{\rho}_{22} = i \frac{\Omega_r}{2} (\rho_{23} - \rho_{21}) + \rho_{11} \frac{\gamma_L}{2}, \tag{7}
\]

\[
\dot{\rho}_{33} = i \frac{\Omega_r}{2} [(\rho_{13} - \rho_{12}) + \Omega_1 (\rho_{23} - \rho_{22})] - \rho_{33} \gamma_L, \tag{8}
\]

\[
\dot{\rho}_{12} = i \frac{\Omega_r}{2} (\rho_{32} - \rho_{13}) + \rho_{12} \left( i\delta - \frac{\gamma_T}{2} \right), \tag{9}
\]

\[
\dot{\rho}_{13} = i \frac{\Omega_r}{2} (\rho_{33} - \rho_{11}) - \Omega_1 \rho_{12} + \rho_{13} \left( i\delta - \frac{\gamma_L}{2} \right), \tag{10}
\]

\[
\dot{\rho}_{23} = i \frac{\Omega_r}{2} [(\rho_{13} - \rho_{22}) - \Omega_r \rho_{21}] - \rho_{23} \frac{\gamma_L}{2}, \tag{11}
\]

where \( \gamma_T \) and \( \gamma_L \) are the transverse and longitudinal spin relaxation rates and \( |1\rangle \equiv | \downarrow, N + 1 \rangle \), \( |2\rangle \equiv | \downarrow, N \rangle \).
and |3⟩ ≡ |↑, N⟩. One solves the system, seeking time independent solutions, by successive approximations to second order in Ωr/Ω1. Taking ρ11 ≈ 1, ρ22 ≈ 0, ρ33 ≈ 0 as initial conditions and assuming that γL ≡ γT for conduction electrons, one obtains

\[ P_{dark} = \frac{4\Omega_1^2 \Omega_r^2}{\Omega_1^2 + \Omega_r^2} \left( \Omega_1^2 + \gamma_L \gamma_T \right) \left( \Omega_1^2 + 2\gamma_L \gamma_T - 4\delta^2 \right)^2 + 4\delta^2(\gamma_L + \gamma_T)^2. \] (12)

The resonant snake orbits are accompanied by spin flips. Blocking their propagation stops spin flips. Conversely if spin flip is not allowed, the Zeeman gap acts as an energy barrier to the propagation of snake orbits—as shown by the temperature dependence in fig. 3. We obtain the microwave-induced resistance by writing the sample conductivity as a sum of two components. One component is the conductivity along the path of snake orbits σs(1 − Pdark). The other component Σ incorporates the conductivity of all other orbits which are not bound by the magnetic potential. The conductivity in the absence of microwaves is σ0 = σs + Σ. The change in longitudinal resistance brought by the formation of the dark state then writes

\[ \Delta \rho_{xx}^W/\rho_0 = \rho_0 \sigma_s P_{dark}. \] (13)

Equation (13) shows that the amplitude of the resistance peak is proportional to the probability of the dark state. The dark state increases the resistance by blocking spin flips and freezing snake orbit drift. We estimate ρ0σs ≈ 1800% ± 360% from the change in resistance caused by suppression of snake orbit channelling [13].

Equations (12) and (13) describe the ESAR peak that results from the coherent interaction of MESR and SESR. We now use these equations to fit the ESAR peak in fig. 5(d). The Rabi frequency that corresponds to a microwave frequency of 110 GHz is obtained as follows. Setting 110 GHz on the vertical axis of fig. 5(a) gives \( \tilde{y} \approx \varepsilon/a \) on the horizontal axis. Reporting this value on the horizontal axis of fig. 5(b) gives a Rabi frequency close to the theoretical maximum. Using the calculated value \( \Omega_1/(2\pi) = 0.81 \text{ GHz} \), we find that eq. (13) fits the width of the peak best for spin scattering rates \( \gamma_L = \gamma_T = 1.76 \times 10^{10} \text{s}^{-1} \). This spin scattering rate is close to the momentum scattering rate \( \mu m^+e/\varepsilon = 1.4 \times 10^{10} \text{s}^{-1} \) which suggests that the spin relaxation time is limited by the lifetime of snake orbits. One also notes that \( \Omega_1 = 0.29\gamma_L \) which indicates that there is sufficient time for spins to flip between two scattering events. This fulfills the condition of quantum coherence required for the formation of the dark state. The fit of the ESAR peak amplitude with eq. (13) gives an estimate of the Rabi frequency \( \Omega_r \) of the MESR transition. The accuracy of the fit is limited by the accuracy on \( \rho_0\sigma_s \) and gives \( \Omega_r/(2\pi) = 70 \pm 15 \text{ MHz} \). The fact that \( \Omega_r \ll \Omega_1 \) can be verified by examining the dependence of the ESAR peak amplitude on microwave power—see fig. 4(b). In this case, eq. (12) predicts that \( P_{dark} \propto \Omega_r^2 \propto \tilde{B}_r^2 \), meaning that the probability of the dark state increases linearly with microwave power. In the opposite case \( \Omega_r \gg \Omega_1 \), \( P_{dark} \) would have been independent of the microwave power.

In summary, magnetic superlattices allow the electrical detection of spin resonance by forming orbits that couple orbital and spin motion. We interpret the resistance peak as the result of the coherent interaction between SESR and MESR which decreases the conductivity of state states. Spatially varying magnetic fields reveal to be an attractive system for coherent spin manipulation.

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