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Integrating magnetism into semiconductor electronics

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Abstract. The view of a ferromagnetic – semiconducting hybrid structure as a single tunable system is presented. Based on an analysis of existing experiments it is shown that, contrary to a 'common sense', a nonmagnetic semiconductor is capable of playing an important role in controlling ferromagnetism. Magnetic properties of a hybrid (the hysteresis loop and the spatial orientation of magnetization) can be tuned both optically and electrically by utilizing semiconductor — making the hybrid an electronic-write-in and electronic-read-out elementary storage unit.

1. Introduction

Most electronic devices rely on flows of electrons (hence the term 'electronics') being controlled by electric and magnetic fields. The electron, in addition to its charge, also possesses an intrinsic angular momentum, or spin. In the language of classical physics, an electron rotates about its own axis. Spin, however, is of quantum origin and can only be oriented either 'up' or 'down' with respect to a specified direction. In today's computers, a bit of information is given by the state of a large ensemble of electrons, all having their spins ordered ferromagnetically (i.e., parallel to one another). The total spin 'up' orientation of the ensemble corresponds to a logical unit, and the total spin 'down' orientation to a logical zero. Recently, the term 'spintronics' was coined to refer to the branch of electronics which utilizes not only the electron charge but also the electron spin to produce functional devices [1]. The first practical application of spintronics made use of the giant magnetoresistance effect discovered by A Fert and coworkers in 1988 [2]: the electrical resistance of a metallic ferromagnetic – paramagnetic – ferromagnetic trilayer structure depends on how the magnetic moments of the two ferromagnetic layers are oriented with respect to one another. It is this effect which lies at the heart of operation of the read heads in hard disks of modern computers [3].

Today, considerable effort is being directed toward integrating magnetism into the semiconductor-based architecture of the modern computer, with a view to developing an entire computer on a single semiconducting chip with a device capable of electronically writing and reading information to and from magnetic materials. Processing information requires an elementary electronic-access magnetic storage unit. One approach to this problem is to develop a universal object which will combine the properties of a ferromagnet (FM) and a semiconductor (SC). In the 1960s, intensive research work was performed on ferromagnetic semiconductors (europium chalcogenides, Cd – Cr spinels) [4]. These, however, possess a major drawback in that they have a low Curie temperature T_C and are poorly compatible with standard Si-, Ge-, and GaAs-based semiconductor technologies. In recent years, there has been an active search for other ferromagnetic semiconductors [5, 6]. The main obstacle here is that a whole number of requirements have to be met within the framework of a single particular structure.

An alternative to this comprises hybrid FM – SC systems [7]. One of the attractions of this approach is that it adds another 'degree of freedom' by allowing an independent choice from an abundance of ferromagnetic materials and standard paramagnetic semiconductors. Another advantage is that the magnetization of an FM can be read out using a semiconductor — by, for example, exploiting the Hall effect or when electrically injecting spin-polarized electrons from the FM to the SC layer in an FM – SC – FM trilayer structure. In the latter case, the electrons of the semiconductor acquire a nonequilibrium polarization which is read out with the aid of a second FM. In both cases, however, the semiconductor plays a passive role, either merely as a substrate or as a detector for the FM magnetization.

The reverse action of the SC on the magnetic properties of the FM seems at first glance to be negligible. Indeed, the charge (and spin) carrier density in a nonmagnetic (paramagnetic) semiconductor is much less than the density of magnetic atoms in metallic ferromagnets and ferromagnetic semiconductors. Thus, the common sense prompts that the

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spin system of the ferromagnet is too powerful for the semiconductor to control. This is not always the case, however. For example, the formation of a junction between a thin ferromagnetic film and a semiconductor causes band bending in the semiconductor (Schottky barrier) and leads to the accumulation of a great many charge carriers (electrons or holes) near the interface. The strong exchange interaction — that is, Coulomb interaction with due regard for Pauli principle — between the charge carriers in the SC and the magnetic atoms in the FM film creates a unified spin system whose magnetic properties differ substantially from those of the film itself. What makes the FM – SC system unique is the ease with which the electrical and magnetic properties of the paramagnetic semiconductor can be optically or electrically varied, thus allowing control over the ferromagnetic properties of the unified system as well (for example, the shape of the magnetic hysteresis loop). As a result, the semiconductor is not just a substrate for the FM: it itself *actively* participates in information processing by reading out and controlling magnetization. The effect of the SC on the FM is stronger for a thinner ferromagnetic film, and it is precisely thin films (a few nanometers across) which are used for high-density recording of information. To summarize, the FM – SC hybrid looks like a promising electronically controlled elementary magnetic storage unit.

This review examines the current status of research on the strongly coupled spin system of the ferromagnet and the semiconductor. It also demonstrates that the spin system of the charge carriers in a semiconductor actively participates in processing information by optical and electrical means.

2. Optical readout and control of magnetism in FM – SC hybrids

The use of a semiconductor in a hybrid system (specifically, in Ni – GaAs) for reading out magnetization and controlling its magnetic properties was first demonstrated 10 years ago in Refs [8, 9], where the authors employed the *nonequilibrium* spin of optically oriented electrons in the semiconductor for readout purposes. A classical optical orientation experiment [10] starts by generating spin-polarized electrons with circularly polarized light which transfers angular momentum to the spin system of the electrons in a semiconductor. If the photoexcited electrons do not lose completely their initial spin polarization during their lifetime, then the radiation accompanying electron annihilation is circularly polarized. The degree ρ of the photoluminescence (PL) circular polarization is equal to the projection of **S** (the ensemble-averaged electron spin) onto the direction of observation z, usually coinciding with the normal to the plane of the structure (Fig. 1). In a magnetic field **H**, each electron spin rotates (or precesses) around the field with the Larmor frequency $\omega = \gamma H$, where γ is the gyromagnetic ratio. In a steady state, the spin **S** is independent of time and tilts from its original direction z, thus decreasing in magnitude and leading to the Hanle effect (the decrease in the degree of PL polarization with an increase in the magnetic field). The half-width $H_{1/2}$ of the magnetic depolarization curve is determined by the condition that the frequency $\gamma H_{1/2}$ be equal to the inverse lifetime $1/T_s$ of a nonequilibrium spin. The longer the lifetime of a nonequilibrium spin T_s, the weaker the magnetic field that is needed for its tilt and for luminescence depolarization. In fact, an optical magnetometer using the Hanle effect is available, whose sensitivity is determined by the magnitude of $H_{1/2}$. The

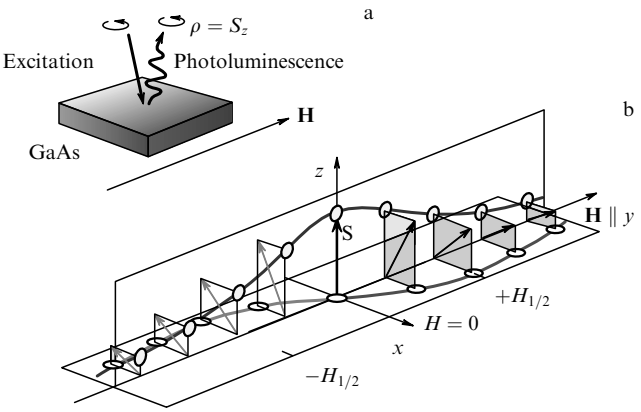

Figure 1. Geometry of an optical orientation experiment (a) and the Hanle effect (b) in a semiconductor. Arrows indicate the average steady-state electron spin **S** in a transverse magnetic field **H** of different strengths. The projection S_z of the spin onto the direction of observation (z-axis) is measured as a function of the magnetic field strength.

half-width $H_{1/2}$ depends strongly on the aggregate state of the material. For example, the optical orientation of paramagnetic atoms in gases persists for a record long time $T_s \sim 1$ s, leading to supersmall values of $H_{1/2} \sim 10^{-6}$ Oe [11, 12], as compared to condensed media, where the spin relaxation time is much shorter due to the enhancement of spin-nonconserving interactions.

In GaAs type semiconductors, the narrowest half-widths $H_{1/2}$ (1 to 10 Oe) are found in n-type GaAs (were $T_s \sim 10^{-8} - 10^{-7}$ s).[1] Information from the magnetic film in the Ni – GaAs system was read out using n-type gallium arsenide in which the half-width was $H_{1/2} = 2$ Oe at a helium temperature [9], corresponding to the spin lifetime $T_s \approx 130$ ns. Stray fields near the surface of the ferromagnet are strongest when the FM film is demagnetized, i.e., is broken up into a large number of domains with their magnetization vectors **M** alternating in direction. Precession in the static fields of the domains leads to electron spin dephasing, thus decreasing the average spin **S** and PL polarization. Figure 2a illustrates the Hanle effect for electrons in gallium arsenide for two cases: the first magnetized (triangles) film, and first demagnetized (circles) film. It is seen that the demagnetization of the sample decreases the degree of PL polarization, the difference being largest for a zero external magnetic field.

The so-called coercive force — the magnetic field strength h_c at which the magnetic moment of the sample becomes zero — can be estimated by measuring the zero-field polarization $\rho(H = 0)$ *after* reversing the magnetization of the ferromagnet by an external field H^*. If the reversing field H^* is equal to h_c, the film is demagnetized, and the PL polarization

[1] Long electron spin memory times, first discovered in n-GaAs in the late 1970s [$T_s \sim 30$ ns, Weisbuch C, *PhD Thesis,* Paris, (1977)], are due to the relatively weak spin-orbit coupling in the conduction band and due to the absence of holes which are normally an efficient source of spin relaxation [10]. Although macroscopic-scale electron spin diffusion lengths L_s of more than 10 μm in n-GaAs were discovered by our team in 1994, the results were published later in a paper by R I Dzhioev et al. (*Fiz. Tverd. Tela* **39** 1975 (1997) [*Phys. Solid State* **39** 1765 (1997)]). In Ref. [9], we used these results by employing GaAs with $H_{1/2} = 2$ Oe ($T_s = 130$ ns), $L_s = 13$ μm, which enabled us to detect the ferromagnetic Ni – GaAs interface just a few nanometers thick, whose stray fields (~ 1 Oe) penetrate deep into the semiconductor (see the main text).

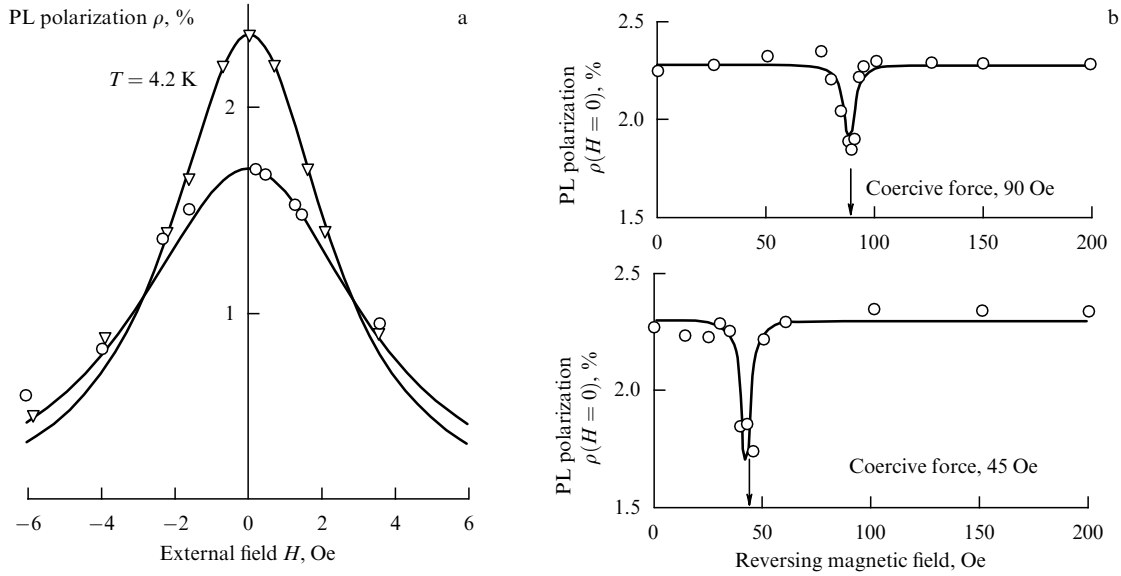

Figure 2. (a) Hanle effect in an Ni–GaAs structure which was preliminary demagnetized (circles) and magnetized (triangles) in a field of 400 Oe. (b) Degree of PL polarization in a zero external magnetic field, $\rho(H = 0)$, as a function of the reversing magnetic field H^*; top: magnetization reversal in darkness; bottom: the same for illumination by an He–Ne laser with an intensity of 5 W cm^{-2}. (Taken from Ref. [9]).

is minimum. The points in the upper curve in Fig. 2b were obtained for a laser beam shut off in the magnetization reversal process — that is, *in the darkness*. The sharp minimum corresponds to the field $h_c = 90$ Oe. The coercive force h_c as measured using the Hanle optical magnetometer was two and a half times that obtained with a superconducting quantum interference device (SQUID). The difference between the two techniques is that a SQUID primarily detects the magnetic moment of the nickel film itself, whose thickness (40 nm) greatly exceeds that (a few nm) of the Ni–GaAs interface. With optical detection, however, the contributions which the stray fields from the nickel and the interface make to electron spin dephasing in GaAs are not just the algebraic sum of the magnetic moments of the nickel and the interface. The reason is that the length of diffusion of a nonequilibrium electron spin into the depths of n-GaAs, $L_s \approx 13$ μm [9], is an order of magnitude larger than the domain size in the nickel film (about 1 μm [13]), so that the fields of the nickel domains decay rapidly close to the surface, thus remaining unsensed by most electrons in the semiconductor. The magnetic fields of the interface domains, on the contrary, penetrate into the semiconductor over a distance $\geqslant L_s$ [9] to produce electron spin dephasing deep within the semiconductor. Thus, we see that the spatial separation of the magnetic stray fields in the nickel and the interface enables the ultrathin Ni–GaAs interface to manifest itself in optical orientation experiments [9].

The important feature of the Ni–GaAs hybrid system is that it enables the interface ferromagnetism to be optically controlled. Whereas the illumination of the sample strongly reduces the coercive force of the interface (see the lower curve in Fig. 2b), it has practically no effect on that of the nickel film. A comparison of the upper and lower curves in Fig. 2b shows that the coercive force under illumination is half that in the darkness. This effect — which we called *photocoercitivity* — is insensitive to polarization of light, and local in the sense that it occurs only in the illuminated region. This allowed information to be optically read out from and written to the Ni–GaAs interface. An originally magnetized sample of Ni–GaAs was exposed to an external reversing magnetic field equal to the coercive field under illumination (45 Oe). This field cannot change the magnetization in darkness, but local illumination by an He–Ne laser resulted in the demagnetization of the illuminated regions. In this way, one can store information as a sequence of ones and zeros represented by the magnetized and demagnetized regions of the structure, respectively. Optical read out was performed in a zero external magnetic field by using optically oriented electrons in GaAs: the electrons beneath the demagnetized and the magnetized regions were polarized weakly and strongly, respectively. The phenomenon of photocoercitivity occurs at weak luminous fluxes (~ 10 mW cm^{-2}) and has nothing to do with the sample being superheated by light [2], as compared to standard thermal recording, in which an FM is heated to near the Curie temperature by light. Spectral measurements demonstrated that the photocoercitivity effect is related to the influence the semiconductor exerts on the ferromagnet: the effect decreases sharply if the photon energy is less than the band gap in GaAs. A possible explanation for photocoercitivity is that light controls the exchange interaction between the electrons of the semiconductor and the magnetic atoms of the FM at the heteroboundary [14].

A body of experimental evidence has been accumulated to date, demonstrating the important role the semiconductor has in optically reading out magnetization [15] and in controlling the coercive field [16]. In the former case, the electrons in the semiconductor acquire a nonequilibrium spin polarization proportional to **M** as a result of spin-dependent electron transport across the FM–SC boundary [17]. In the latter case, the illumination of the InMnAs–GaSb hybrid changes the coercive force of the InMnAs film. Paper [16] reports a significant decrease in the coercive force in the case where the light quantum energy $h\nu$ exceeds the band gap E_g of the nonmagnetic GaSb semiconductor. The fact that the

[2] This was checked experimentally by passing a current through the FM–SC boundary when reversing the magnetization [9]. The coercive force of the interface remained unchanged even though the power dissipated at the boundary was ten times the light power.

effect drops off for $h\nu$ close to E_g points to the key role of the semiconductor.

Mention should be made here of the work on photo-induced ferromagnetic ordering in the InMnAs – GaSb system [18]. It has been found that the excitation of GaAs causes a paramagnet-to-ferromagnet transition in the magnetic InMnAs semiconductor — a phenomenon which can be interpreted as a photo-induced increase in the Curie temperature. This effect is known in ferromagnetic semiconductors [4], but in this particular case it is caused by the influence of the nearby nonmagnetic semiconductor.

Yet another class of phenomena is the magnetization of a ferromagnetic GaMnAs film by circularly polarized light. The effect was discovered in the GaMnAs – GaAs system [19] and is explained by the authors as being due to the creation in GaMnAs of spin-oriented holes which polarize the spins of Mn atoms. However, the steep spectral dependence of the effect correlates with the absorption edge of the paramagnetic GaAs rather than of the magnetic GaMnAs whose absorption edge is shifted toward higher energies already at low Mn concentrations of $\sim 1\%$ [20]. This fact implies that gallium arsenide plays a key role in the optical magnetization of GaMnAs.

Theoretically, the magnetization of a ferromagnet by circularly polarized light may be due to the exchange interaction between the magnetic atoms and the optically oriented holes in the enriched GaAs layer near the FM – SC heteroboundary [21], with the result that the FM experiences the effective magnetic field $\mathbf{H}_{\text{eff}}$ whose direction is determined by the spirality of the photons being absorbed [3] [21, 22].

3. Electric readout and control of magnetism in FM – SC hybrids

To fully integrate the FM into semiconductor electronics requires that information be read out and written not only and not so much optically as electrically.

Two main approaches to the semiconductor-assisted electric readout of magnetization are currently recognizable. The first approach exploits the fact that the resistance of an FM – SC – FM trilayer structure [1] depends on the relative orientation of the FM magnetizations — whether because semiconductor tunnel barriers act differently for 'up' and 'down' spins or because nonequilibrium spins accumulate in the semiconductor due to the injection of polarized electrons through the ferromagnetic metal – semiconductor junction [23]. With the second approach, readout is even possible for FM – SC bilayer structures. Underlying the approach is spin – orbit interaction, whose physical nature is as follows. The spin of a charge carrier moving in an electric field is subjected to an effective magnetic field whose vector (magnitude and direction) is determined by the values and directions of the charge carrier velocity and external electric field. Because of the spin – orbit coupling, the in-layer electrical conduction in the hybrid FM – SC system depends on the mutual orientation of the electric current and the magnetic moment. For example, the anomalous Hall effect (i.e., the dependence of the Hall coefficient on the magnetization **M**) is widely used [24] to detect the spin polarization in ferromagnetic and nonmagnetic semiconductors.

[3] We also note that the $\mathbf{H}_{\text{eff}}$ field causes the magnetic hysteresis loop to shift. If $H_{\text{eff}} > h_c$, circularly polarized light can fully magnetize the FM even in the absence of an external magnetic field.

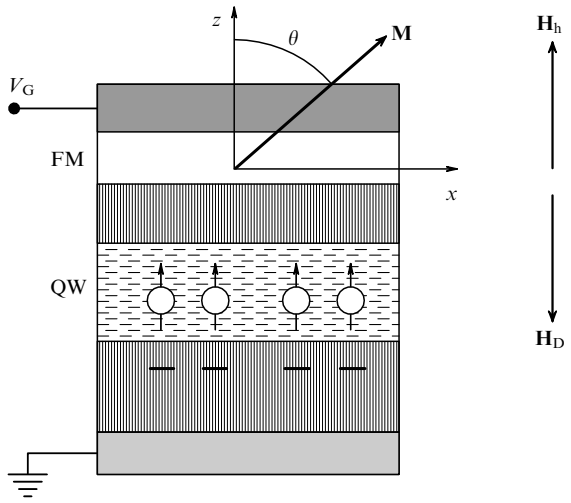

Figure 3. Schematic of a structure operating on a basis of the exchange coupling effect in the FM – SC hybrid. A semitransparent barrier (shown dashed vertically) separates the FM from the quantum well (QW). Gate bias V_G controls the exchange coupling between the FM and the holes (white circles) in the QW. Arrows in the QW indicate the spin orientation of heavy holes. (Taken from Ref. [25]).

An important step toward an electronic-access magnetic storage unit is to use a semiconductor for electrical *control* of ferromagnetism. The magnetic moment of the FM – SC hybrid can be reoriented electrically owing to the exchange coupling between the spin systems of the ferromagnet and the semiconductor [25]. Let us consider, for the case of no external magnetic field, the exchange interaction between the magnetic atoms in the FM and the hole gas in a quantum well (QW) adjacent to the SC (Fig. 3). The quantum well is formed of a thin layer of a narrow bandgap semiconductor sandwiched between two layers of wide bandgap materials (shown dashed vertically), which act as barriers that confine carrier motion in the direction of growth in a region less than the de Broglie wavelength across (dimensional quantization). The selective doping of the lower barrier with acceptors (shown as dashes in Fig. 3) creates hole-type carriers (white circles) in the quantum well. The hole states in the valence Γ_8 band in GaAs type semiconductors are described by the total angular momentum of 3/2. The strong spin – orbit interaction combined with the dimensional quantization causes the valence band to split, with the ground state corresponding to the so-called heavy holes having their spins rigidly oriented along the axis of the structure. In this case [26], the exchange interaction between the spin systems of the magnetic atoms in the FM and of semiconductor's holes (which is characterized by the constant J) is anisotropic: the energy per unit surface, $E_{\text{exc}} = -Jnm_zS_z$, is proportional to the product of the z-component of the average spin **S** of holes (with a surface concentration n) and the z-component of the unit vector **m** along the magnetization vector **M**. The exchange interaction splits the bands of spin-up and spin-down holes by an amount $J \sim 0.1$ eV, leading to their high spin polarization $S_z \sim 1$. The polarized holes, in their turn, create a field $\mathbf{H}_h$ which acts in equilibrium to direct the vector **M** along the normal, thereby lowering the energy E_{exc}. The magnitude of this field is determined by equating E_{exc} to the interaction energy $-M_zH_hd$ between the magnetization and the effective field: $H_h = JnS_z/Md$ (where d is the film thickness). However, the magnetostatic energy of the film, which is due to the magneto-

dipole interaction, increases as the vector **M** leaves the plane. Because the normal component of the magnetic induction vector **B** is continuous at the FM–SC boundary ($B_z = H + 4\pi M_z = 0$), it follows that quitting the plane produces a demagnetizing field of strength $H_D = -4\pi M_z$ ($H_D \sim 1$ kOe) [27]. The equilibrium configuration is one in which the exchange and demagnetizing fields are equal. [4] This allows one to estimate the ratio of the surface concentration n of the holes in the well to that of the magnetic atoms, $N \approx Md/\mu_B$, which is needed to control the magnetization orientation in the FM: $n/N \approx \mu_B H_D/JS_z \approx 10^{-4}$. In other words, it takes only one hole to control ten thousand (!) magnetic atoms. The physical explanation for this surprising (at first sight) result is that the anisotropic exchange interaction between the FM and SC overcomes the relatively weak magneto-dipole interaction. This leaves the exchange energy of the FM itself unchanged [5], because the atomic spins in the FM all rotate in such a way as to keep their parallel orientation intact: the isotropic exchange interaction inside the FM specifies the magnitude, not the direction, of the **M** vector. Unlike the FM, in the semiconductor the strong spin–orbit interaction in the valence band combines with dimensional quantization to fix the direction along which the spins of the holes align. In equilibrium, the polarized holes create an easy-magnetization axis in the FM along the normal, and the energy E_{exc} can be considered as the magnetic anisotropy energy. This energy can be controlled, either by applying a bias V_G to the gate (Fig. 3), by varying the concentration of holes in the quantum well, or by varying their wave function overlapping with the magnetic layer (i.e., the value of J).

The exchange coupling between the spin systems of the ferromagnetic MnAs layer, on the one hand, and of holes in the semiconductor GaAs quantum well, on the other hand, was experimentally examined [28] in the form of circularly polarized PL from a quantum well. It was found that the exchange interaction does indeed give rise to equilibrium hole polarization (about 10%) and that this polarization can be controlled electrically. The electrical control of ferromagnetism had been achieved earlier [29] in ferromagnetic InMnAs grown on a layer of the paramagnetic InAs semiconductor. The hysteresis loop of the InMnAs was changed by applying a bias to the gate deposited on the ferromagnet. The cardinal change in the hysteresis loop structure is, the authors of Ref. [29] believe, due to a small change in the Curie temperature $T_C(V_G)$ with hole concentration *within* the InMnAs itself. In our view, however, this requires further verification. [6] An alternative explanation suggested in Ref. [25] involves exchange interaction of the FM with the holes in a nonmagnetic InAs layer 5 nm thick. The InMnAs–InAs structure should in this case be considered as a strongly coupled hybrid system. Applying a negative bias causes the holes to fill the InAs layer, inducing an easy axis along the normal and thereby giving rise to a hysteresis phenomenon in the magnetic field parallel to the normal (perpendicular anisotropy). When the gate bias is positive, holes leave the InAs, the vector **M** lies in the plane of the film, and magnetization by an external field shows no hysteresis. In favor of this explanation is the fact that removing the nonmagnetic InAs layer makes magnetization nonhysteretic [30]. What is needed to verify this explanation is to determine the total orientation of the vector **M** in space rather than its z-component alone [29].

The electrical restructuring of the magnetic anisotropy energy also changes the energy of the domain boundary, which, in turn, can affect the coercive force. [7] A recent study [31] on a perpendicularly anisotropic InMnAs–InAs structure has demonstrated that the width of the hysteresis loop can be controlled by varying the electric field and keeping the saturation magnetization constant. The fivefold change in coercive force is hard to explain by a small (a few percent) change in the Curie temperature and hole concentration in the bulk of the InMnAs. The FM–SC coupling, on the contrary, does account for the result of Ref. [31]: the gate bias controls the magnetic anisotropy energy and thereby the coercive field.

4. Ferromagnet magnetization reversal using a semiconductor

We have seen above that, when in equilibrium, a semiconductor and a ferromagnet form a unified, strongly coupled spin system whose magnetic properties can be controlled either optically or electrically using a nonmagnetic semiconductor. The next bold step is to control the magnetic moment of the FM *dynamically* with the aid of the semiconductor. Figure 4 below illustrates the physics of this idea [25]. Suppose the system departs from equilibrium (Fig. 4a) due to the vanishing of the field H_h. Then the magnetic moment rotates (Fig. 4b) about the direction of the reversing magnetic field in a coherent manner, with angular frequency $\omega = \gamma H_D$ and precession period $T = 2\pi/\omega = (2\gamma M_z)^{-1}$. A half a period

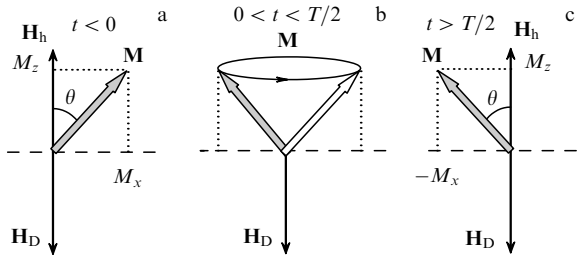

Figure 4. Controlling the orientation of the **M** vector by varying the field $\mathbf{H}_h$ in a pulsed manner: (a) stable equilibrium before pulse application, $t < 0$. The orientation of magnetization in the plane $M_x > 0$ is fixed by the direction of the easy-magnetization x-axis (see footnote 4); (b) the field $\mathbf{H}_h$ jumps to zero. In the time interval $[0, T/2]$, the vector **M** precesses around the demagnetizing field $\mathbf{H}_D$, and (c) at the end of the pulse (the field $\mathbf{H}_h$ takes on the original value), the system resides in a stable state with the value of M_x inverted.

[4] We assume here that spin–orbit effects in the ferromagnet are weak, just strong enough for *keeping* the vector **M** in the plane of the film (along the x-axis). In the original work [25], on the contrary, uniaxial in-plane anisotropy due to spin–orbit interaction was assumed.

[5] In fact, it does change a little, resulting in a slightly changed Curie temperature (see Ref. [4]).

[6] The authors of Ref. [29] control the hysteresis loop in one sample (see Fig. 3 in their paper), while measuring the $T_C(V_G)$ dependence on the other (their Fig. 4).

[7] The possibility of electrically controlling the magnetic anisotropy energy and the coercive force in FM–SC hybrids, which was first discussed in Ref. [9], derives from the combination of the piezoelectric properties of a GaAs-type semiconductor (which has no inversion center) with the magnetostriction property of the ferromagnet — that is, varying the electric field near the FM–SC boundary changes both the structure deformation and magnetic anisotropy in the plane of the film. To our knowledge, this effect has not yet been observed. Note that the effect can also occur in a bulk ferromagnet possessing piezoelectric properties — for example, in ferromagnetic GaMnAs (InMnAs) semiconductors which, like GaAs, have no inversion center.

($T/2$), later the magnetization component in the plane of the film is inverted. Reestablishing the exchange coupling between the FM and QW at this moment of time will make the state with an inverted M_x component to be a stable one (see footnote 4). To see this, note that if the spin relaxation time of the holes is short, then both the hole polarization and the exchange field H_h rapidly return to their previous values at the end of a pulse, and the magnetization orientation is as shown in Fig. 4c. The field H_h can be turned off by applying voltage pulses V_G to the gate (see Fig. 3), and the precession period can be controlled by tuning the z-component of magnetization via variation of the hole concentration in the QW before applying the pulse. For example, for $M_z = 25$ Oe, the time $T \sim 1$ ns.

The crucial point about the controlled magnetism concept proposed is that it does not involve employing huge current densities on the order of 10^5 to 10^8 A cm^{-2}, used in semimetal [32] and metal [33] systems: it is the effect of an electric field which underlies this approach. Another point is the ease with which the requirement for the fast establishment of equilibrium in the spin system of a semiconductor is satisfied at elevated temperatures [10]. While a major disadvantage for schemes relying on nonequilibrium spin [1], this property becomes advantageous with this approach. The departure from equilibrium takes place in the spin system of the ferromagnet (but not of the semiconductor) during the time period τ it takes the vector **M** to turn through 180°. Therefore, the time it takes **M** to return to equilibrium (i.e., the relaxation time) *inside* the FM itself should exceed τ. The relaxation time in common metal ferromagnets is not large (about 1 ns according to Ref. [34]), so nonmetallic FMs are a better choice for this purpose (for nickel ferrites at room temperature, the relaxation time is on the order of 100 ns [27]).

In another approach, the magnetization orientation can be controlled optically, by illuminating the system with circularly polarized light. As noted above, this may have to do with the optical orientation of charge carriers in the hybrid FM – SC structure. This gives rise to an effective exchange magnetic field [21, 22] — in this case, a pulsed one — which causes the coherent rotation of magnetization. Recent experiments [35] on the optical pulse excitation of GaMnAs – GaAs have revealed a collective precession of a large number of manganese spins in ferromagnetic GaMnAs. However, further study is needed to establish the nature of the effect observed.

5. Conclusions

In summary, we have presented a view of the FM – SC hybrid as a single tunable system. There is a whole series of experiments that can be interpreted in terms of a strongly coupled spin systems of the ferromagnet and the semiconductor. The unified system is unique in that its magnetic properties can be modified by electrical or optical methods. The FM – SC system constitutes an elementary magnetic storage unit in which the semiconductor not only serves as a substrate, but also actively participates in information processing. The freedom of choice for selecting a desired FM – SC pair from paramagnetic semiconductors and a large number of ferromagnets offers a range of possibilities. In the very near future, new hybrid FM – SC systems are expected to be developed, as are new means for optically and electrically writing and reading information to and from them. With the semiconductor-assisted dynamical control of magnetization, the integration of magnetism into semiconductor electronics will become a reality. The enthusiasm currently being shown in this field is reminiscent of the search in the 1960s for an ideal pair of semiconductors with which to create the heterojunction and semiconductor heterolasers. The search for an ideal FM – SC pair today is a no less interesting and important task.

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