Long-range $p-d$ exchange interaction in a ferromagnet–semiconductor hybrid structure

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Hybrid structures synthesized from different materials have attracted considerable attention because they may allow not only combination of the functionalities of the individual constituents but also mutual control of their properties. To obtain such a control an interaction between the components needs to be established. For coupling the magnetic properties, an exchange interaction has to be implemented which typically depends on wavefunction overlap and is therefore short-ranged, so that it may be compromised across the hybrid interface. Here we study a hybrid structure consisting of a ferromagnetic Co layer and a semiconducting CdTe quantum well, separated by a thin (Cd,Mg)Te barrier. In contrast to the expected $p-d$ exchange that decreases exponentially with the wavefunction overlap of quantum well holes and magnetic atoms, we find a long-ranged, robust coupling that does not vary with barrier width up to more than 30 nm. We suggest that the resulting spin polarization of acceptor-bound holes is induced by an effective $p-d$ exchange that is mediated by elliptically polarized phonons.

Exchange interactions are the origin for correlated magnetism in condensed matter with multi-faceted behaviour such as ferro-, antiferro- or ferrimagnetism. In magnetic semiconductors (SCs), the exchange occurs between free charge carriers and localized magnetic atoms and is determined by their wavefunction overlap. To control this overlap, hybrid structures consisting of a ferromagnetic (FM) layer and a semiconductor quantum well (QW) are appealing objects because they allow wavefunction engineering. Furthermore, the mobility of QW carriers will not be reduced by inclusion of magnetic ions in the same spatial region in these systems.

More specifically, for a two-dimensional hole gas (2DHG, the $p$-system) in a QW the overlap of the hole wavefunction with the magnetic atoms in a nearby ferromagnetic layer (the $d$-system) is believed to result in $p-d$ exchange interaction$^{1-4}$. This exchange interaction may cause strong coupling between the SC and FM spin systems$^5$, through which the ferromagnetism of the unified system, as evidenced by its hysteresis loop, can be tuned. In particular, the 2DHG spin system becomes polarized in the effective magnetic field from the $p-d$ exchange$^4$. Recently$^6$, it was shown that in addition to this equilibrium 2DHG polarization there is an alternative mechanism involving spin-dependent capture of carriers from the SC into the FM. For ferromagnetic (Ga,Mn)As on top of an (In,Ga)As QW, electron capture induces electron spin polarization in the QW, representing a dynamical effect in contrast to the exchange-induced equilibrium polarization.

Here we study a different FM/QW hybrid, consisting of a Co layer and a CdTe II–VI semiconductor QW, separated by a nanometre-thick barrier. Owing to the negligible hole tunnelling through the barrier, this hybrid combination shows mostly a quasi-equilibrium proximity effect due to $p-d$ exchange interaction between magnetic atoms and holes in the QW. Surprisingly, however, the observed proximity effect, assessed through the spin polarization of acceptor-bound holes in the QW, is almost constant over distances as large as the 30 nm spacer width. In contrast, for conventional $p-d$ exchange based on wavefunction overlap, an exponential decay with barrier width with a decay length of about a nanometre would be expected. This exchange coupling is therefore truly long-ranged, which is highly advantageous because it is robust with respect to hybrid interface variations. As origin of the long-range proximity effect we suggest an effective $p-d$ exchange interaction mediated by elliptically polarized phonons near the FM/SC interface.

**FM-induced circular polarization of the QW luminescence**

We study hybrid structures composed of a Co layer and a (Cd,Mg)Te-based layer sequence. This sequence consists of a (Cd,Mg)Te spacer, separating a CdTe QW from the Co, followed by another (Cd,Mg)Te barrier that was grown on top of a (100)-oriented GaAs substrate (see Fig. 1a for sketch of the structures). A set of structures with widely varying parameters was grown. In structure 1 the (Cd,Mg)Te spacer thickness $d_s$ increases continuously from 5 nm to 15 nm over a lateral structure size of 5 cm (wedge shape), and the Co film has a thickness of 7 nm. The semiconducting parts of the other structures are similar to those of structure 1, except for the spacer thickness $d_s$, which varies over a 3 cm lateral dimension from a thickness of zero to 10 nm for structure 2, from zero to 14 nm for structure 3, and from 10 up to 40 nm for structure 4. In addition, the Co-film thickness, $d_{cw}$, is varied in discrete steps of 1 nm from zero to 6 nm normal to the spacer thickness gradient (Fig. 1a), followed by an area with a constant Co-film thickness of 16 nm. Atomic force microscopy on structure 2 with a 5-nm-thick Co layer shows a non-uniform Co growth, with islands having lateral sizes of tens of nanometres (Fig. 1b). In the following we present experimental data mainly for structure 2, if not mentioned otherwise. We note that the key observations concerning the proximity effect are similar for all structures.

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The magnetization of the Co layers is oriented in-plane. An out-of-plane magnetization component can be induced by applying an external magnetic field in the Faraday geometry $B_F$ (longitudinal field parallel to the structure growth axis $z \parallel [001]$). In all cases, the Co layers are semitransparent for laser light exciting the sample along $z$ in either linear (α) polarization, or unpolarized using a depolarizing wedge. The band structure of the hybrid system is sketched in Fig. 1c. For photon energies less than the band gap energy $E_{gap} = 2 \text{eV}$ of the barrier, only the QW is excited (Fig. 1a). The photoluminescence (PL) emitted by the QW is analysed with respect to its circular polarization $c_\pi$, to determine the degree of circular polarization $\rho^{c_\pi}$ of the PL under $\pi$-excitation. We also use the polarization difference $\delta \rho^{c_\pi}_\pi(B) = [\rho^{c_\pi}_\pi(B_F) + B_F] - [\rho^{c_\pi}_\pi(-B_F)]/2$ for oppositely oriented fields as a measure of the field-induced signal.

Figure 1d shows $\delta \rho^{c_\pi}_\pi$ recorded for $B_F = 10 \text{mT}$ (blue dots) as a function of the detection energy for a spacer thickness $d_s = 10 \text{nm}$ at a temperature $T = 2 \text{K}$. For comparison the PL spectrum is shown (black line), exhibiting two main lines, one deduced a hole–acceptor binding energy of $10 \text{meV}$ and the $30 \text{meV}$ exciton binding energy of $12 \text{meV}$, which agrees well with values reported for a hole bound to a shallow acceptor in CdTe (refs 11,12).

The circular polarization $\rho^{c_\pi}_\pi(B_F)$ of the PL varies considerably ($\delta \rho^{c_\pi}_\pi$) with characteristic length $d_0 = 1.6 \text{nm}$. Open circles show the spacer thickness dependence of the proximity effect amplitude $A \equiv \delta \rho^{c_\pi}_\pi(B_{FM})$, for the different structures, which seems to be slowly varying.

Time-resolved PL (TRPL) gives insight into the kinetics of the spin polarization after linearly polarized, pulsed excitation. Spectrally resolved PL intensity transients are shown in Fig. 2a, from which we derive the temporal dependence of the FM-induced $\delta \rho^{c_\pi}_\pi(t)$ in Fig. 2b for a magnetic field of $10 \text{mT}$, applied in the Faraday geometry: $\delta \rho^{c_\pi}_\pi(t)$ increases continuously with time. Initially being non-polarized, the photo-excited carriers acquire spin polarization with a characteristic rise time of $\tau_{\text{FM}} \approx 2 \text{ns}$, obtained from an

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**Figure 1** | Ferromagnet-induced proximity effect. **a**, Scheme for the optical excitation of the double gradient structure 2. **b**, AFM image of structure 2 with a Co-film thickness $d_{Co} = 5 \text{nm}$. **c**, Band structure of the investigated structures. The violet arrow indicates the excitation energy, whereas the green and red arrows correspond to PL from the QW and GaAs substrate, respectively. **d**, PL spectrum (black line) and polarization difference $\delta \rho^{c_\pi}$ (blue dots) between the circular polarizations $\rho^{c_\pi}_\pi$ measured for $B_F = 10 \text{mT}$ at $T = 2 \text{K}$; data recorded for linearly polarized pulsed excitation with a photon energy of $1.69 \text{eV}$ and an excitation density $20 \text{W cm}^{-2}$. CdMgTe spacer thickness $d_s = 10 \text{nm}$ and Co thickness $d_{Co} = 4 \text{nm}$. **e**, $\rho^{c_\pi}_\pi(B_F)$ detected at the lower energy flank of the e–A$^0$ transition in the QW around $1.59 \text{eV}$, as indicated by the vertical arrow in (d) (green circles) and the GaAs substrate at $1.49 \text{eV}$ (red triangles); an up–down field scan revealed no hysteresis. **f**, Dependence of the exciton PL intensity on spacer thickness $d_s$ for $d_{Co} = 4 \text{nm}$ (red squares). The dashed line is an exponential fit, $\exp(d_s/d_0)$, with characteristic length $d_0 = 1.6 \text{nm}$. The open circles show the spacer thickness dependence of the proximity effect amplitude $A \equiv \delta \rho^{c_\pi}_\pi(B_{FM})$, for the different structures, which seems to be slowly varying.
not live long enough to acquire polarization from the FM (another possible contribution will be discussed below).

To understand the origin of the FM-induced PL polarization from the QW we have to address the following three questions: Are the electrons or the holes in the QW polarized? Does spin-dependent capture of carriers from the QW into the FM play a role? Is there an effective exchange magnetic field exerted by the FM that polarizes the QW carriers?

**FM-induced spin polarization of the QW heavy holes.** As discussed, application of a longitudinal magnetic field $B_f$ causes polarization of the PL. We apply an additional transverse magnetic field $B_t$ in the Voigt geometry with the goal to depolarize the FM-induced PL polarization (see scheme in Fig. 3a). Figure 3b shows that for $B_t = 4\,\text{mT}$ the polarization difference $\delta \rho^c$ of the QW PL is about 1%, and not sensitive to $B_t$ up to 20 mT. This means that any out-of-plane component $M_z$ of the FM magnetization remains fixed in this range of Voigt fields. However, there is a further important consequence. The data also indicate heavy-hole polarization as source of the non-zero $\delta \rho^c$. Indeed, if $\delta \rho^c$ arose from electron spin orientation, the Hanle effect\(^{14}\) should be observed for the electron spins; for electrons with spins polarized along the $z$-axis the magnetic field $B_t$ would induce Larmor precession about $B_t$. This precession would decrease the $z$-component of the electron spin, leading to a PL depolarization $\rho^c (B_t)$ in complete analogy with the Hanle effect observed for optical injection of polarized electron spin. Indeed, under circularly polarized excitation the degree of polarization $\rho^c (B_t)$ decreases with $B_t$ (green filled circles in Fig. 3c) with a halfwidth $B_{1/2} \approx 15\,\text{mT}$. However, this decrease is absent for $\rho^c (B_t)$ in the same field range (Fig. 3b). Moreover, Fig. 3c shows that application of a 4 mT longitudinal field does not change the Hanle curve (the magenta triangles), which means that the magnetization of the FM does not create a magnetic field (for example, due to $s$–$d$ exchange) that could influence the Larmor precession of the electron spin. Therefore, the out-of-plane magnetization $M_z$ of the FM neither orients electron spins, nor affects their Larmor precession frequency. We conclude that the FM-induced polarization $\rho^c$ is directly related to spin polarization of the heavy holes: the in-plane $g$-factor of the heavy holes is close to zero, such that the $B_t$ field cannot depolarize them\(^{14}\).

**Figure 2 | Time-resolved spin dynamics.** (a) Contour plot of the PL intensity decay from the QW. The frame indicates the region of interest for polarization measurements corresponding to the e–A\(^0\) transition. (b) Dynamics of the FM-induced proximity effect. The time evolution of the difference of circular polarization degree $\delta \rho^c$ for $B_t = 40\,\text{mT}$ under linearly polarized excitation is shown. The dashed line is a fit according to $\delta \rho^c (t) = A_{\infty} [1 - \exp (-t/\tau_{\text{deph}})]$ with $\tau_{\text{deph}} \approx 2\,\text{ns}$ and $A_{\infty} = 6.5\%$. (c) Optical orientation kinetics. The average circular polarization under excitation by $\sigma^+$-polarized light $\mathbf{P}^c (t) = \rho^c (B_t, t) + \rho^c (B_t, t)/2$ is shown for $B_f = 40\,\text{mT}$ (blue triangles) and $B_f = 0$ (orange circles). The red dashed line gives a double exponential fit to the data for $B_t = 40\,\text{mT}$ with $\mathbf{P}^c (t) = \rho_{0h} \exp (-t/\tau_{\text{sh}}) + \rho_{0e} \exp (-t/\tau_{\text{se}})$, where $\rho_{0h} = 7\%$, $\tau_{\text{sh}} = 0.12\,\text{ns}$, $\rho_{0e} = 11.5\%$ and $\tau_{\text{se}} > 20\,\text{ns}$.

exponential fit (dashed line). In combination with the decay times of 50 ps for the X-line and a few ns for the e–A\(^0\)-line, this allows us to explain the absence of polarization for the X-line: the exciton does

1. $\tau_d$: only the e–A\(^0\) shows the optical orientation $\delta \rho^c$.
2. $\tau_{\text{deph}}$: only the e–A\(^0\) shows that $\delta \rho^c$.
3. $\delta \rho^c$: about $1\%$, and not sensitive to $B_t$ up to 20 mT. This means that any out-of-plane component $M_z$ of the FM magnetization remains fixed in this range of Voigt fields. However, there is a further important consequence. The data also indicate heavy-hole polarization as source of the non-zero $\delta \rho^c$. Indeed, if $\delta \rho^c$ arose from electron spin orientation, the Hanle effect\(^{14}\) should be observed for the electron spins; for electrons with spins polarized along the $z$-axis the magnetic field $B_t$ would induce Larmor precession about $B_t$. This precession would decrease the $z$-component of the electron spin, leading to a PL depolarization $\rho^c (B_t)$ in complete analogy with the Hanle effect observed for optical injection of polarized electron spin. Indeed, under circularly polarized excitation the degree of polarization $\rho^c (B_t)$ decreases with $B_t$ (green filled circles in Fig. 3c) with a halfwidth $B_{1/2} \approx 15\,\text{mT}$. However, this decrease is absent for $\rho^c (B_t)$ in the same field range (Fig. 3b). Moreover, Fig. 3c shows that application of a 4 mT longitudinal field does not change the Hanle curve (the magenta triangles), which means that the magnetization of the FM does not create a magnetic field (for example, due to $s$–$d$ exchange) that could influence the Larmor precession of the electron spin. Therefore, the out-of-plane magnetization $M_z$ of the FM neither orients electron spins, nor affects their Larmor precession frequency. We conclude that the FM-induced polarization $\rho^c$ is directly related to spin polarization of the heavy holes: the in-plane $g$-factor of the heavy holes is close to zero, such that the $B_t$ field cannot depolarize them\(^{14}\).

**Figure 2 | Time-resolved spin dynamics.** (a) Contour plot of the PL intensity decay from the QW. The frame indicates the region of interest for polarization measurements corresponding to the e–A\(^0\) transition. (b) Dynamics of the FM-induced proximity effect. The time evolution of the difference of circular polarization degree $\delta \rho^c$ for $B_t = 40\,\text{mT}$ under linearly polarized excitation is shown. The dashed line is a fit according to $\delta \rho^c (t) = A_{\infty} [1 - \exp (-t/\tau_{\text{deph}})]$ with $\tau_{\text{deph}} \approx 2\,\text{ns}$ and $A_{\infty} = 6.5\%$. (c) Optical orientation kinetics. The average circular polarization under excitation by $\sigma^+$-polarized light $\mathbf{P}^c (t) = \rho^c (B_t, t) + \rho^c (B_t, t)/2$ is shown for $B_f = 40\,\text{mT}$ (blue triangles) and $B_f = 0$ (orange circles). The red dashed line gives a double exponential fit to the data for $B_t = 40\,\text{mT}$ with $\mathbf{P}^c (t) = \rho_{0h} \exp (-t/\tau_{\text{sh}}) + \rho_{0e} \exp (-t/\tau_{\text{se}})$, where $\rho_{0h} = 7\%$, $\tau_{\text{sh}} = 0.12\,\text{ns}$, $\rho_{0e} = 11.5\%$ and $\tau_{\text{se}} > 20\,\text{ns}$. Note that the zero-field decay of $\mathbf{P}^c (t)$ in Fig. 2c contains an additional contribution with $\tau_{\text{sh}} \approx 1\,\text{ns}$ due to electron spin dephasing in the randomly oriented stray fields of the FM with strengths of $\sim 15\,\text{mT}$. The stray fields also determine the 15 mT width of the Hanle curve (see Supplementary Section A2). The dephasing determines the spin dynamics and leads to the faster decay of $\mathbf{P}^c (t)$ at $B_f = 0$. Application of a $B_t = 40\,\text{mT}$ Faraday field suppresses the stray field impact. The comparison of $\mathbf{P}^c (t, B_t = 40\,\text{mT})$ with $\delta \rho^c$ shows that the FM-induced polarization kinetics is much faster ($\tau_{\text{sh}} \approx 2\,\text{ns}$) than the electron spin kinetics ($\tau_{\text{se}} > 20\,\text{ns}$), in agreement with the hole spin-flip being much faster than that of the electron\(^{11}\). However, it is still considerably slower than the hole spin-flip time of $\tau_{\text{sh}} = 0.12\,\text{ns}$. This faster spin relaxation of the optically oriented holes can be explained by the higher laser photon energy (1.70 eV) with which free holes are excited. Optically excited hot holes become depolarized before they are trapped by acceptors. Here we recall the unusual proximity effect shown in Fig. 1d: only the e–A\(^0\) transition shows a FM-induced
Circular polarization, $c\sigma(\%)$

$\rho$ Difference, $\langle \delta c\pi \rangle (\%)$

$\rho$

Figure 3 | Ferromagnet-induced spin polarization of the QW heavy holes bound to acceptors.

a. Sketch of the experiment in crossed magnetic fields. b. Sample 1. Dependence of $\delta c\pi(B_V)$ on magnetic field in the Voigt geometry in the presence of a longitudinal field $B_L = 4$ mT. c. Hanle effect $\rho c\pi(B_V)$ in the absence of a longitudinal field (green circles) and in the presence of a longitudinal field $B_L = 4$ mT (magenta triangles). d. Sample 2, $d_s = 10$ nm. Upper panel: kinetics $\langle \delta c\pi(t) \rangle = [\delta c\pi(t, +B_V) + \delta c\pi(t, -B_V)]/2$ of the proximity effect at $B_V = 96$ mT, $B_L = 10$ mT. Bottom panel: kinetics $\tau \pi (t)$ of the optical orientation in a magnetic field of $B_V = 96$ mT for $B_L = 0$ (green circles) and $B_L = 10$ mT (magenta triangles). The dashed line is a fit according to $\tau \pi (t) = \rho_{0h} \exp(-t/\tau_{sh}) + \rho_{0e} \exp(-t/\tau_{dep}) \cos(g_{e/\mu B} B_V t/I) + C$, with $\rho_{0h} = 8\%$, $\tau_{sh} = 0.15$ ns, $\rho_{0e} = 5\%$, $|g_e| = 1.2$, $\tau_{dep} = 1$ ns, $C = 1.5\%$. $T = 2$ K. Error bars represent standard deviations.

polarization. Hence $\rho c\pi(t)$ reflects the spin kinetics of holes bound to acceptors, whose spin-flip time can be considerably longer than $\tau_{sh}$.

Further evidence (Fig. 3d, upper panel) of the heavy-hole polarization comes from the non-oscillating signal $\delta c\pi(t, B_L = 10$ mT), which increases with time in spite of the large magnetic field $B_V = 96$ mT applied in the Voigt geometry. In contrast, the optical orientation signal $\tau \pi (t, B_L = 10$ mT) oscillates in time in accordance with the electron $g$-factor, $|g_e| = 1.2$, and tends to zero (Fig. 3d, bottom panel).

We conclude that: the out-of-plane magnetization component of the FM is robust in magnetic fields $B_V < 100$ mT; and the FM-induced PL polarization $\rho c\pi(B_V)$ in a longitudinal field originates from spin polarization of heavy holes bound to acceptors.

Spin-dependent capture as possible source of polarization. According to ref. 10 the observed proximity effect may be due to spin-dependent carrier capture from the semiconductor into the FM. In this case, the total PL intensity $I^\pm$ (the sum of the right- and left-circular polarized PL components) in a longitudinal magnetic field would depend on the helicity $\sigma^\pm$ of the exciting light. The intensity modulation parameter $\eta = (I^+ - I^-)/(I^+ + I^-)$ is determined by the parameter $P$, $(h\nu)$ characterizing the selection rules for the involved optical transitions at the laser energy $h\nu$. 
The $p$–$d$ exchange from the overlap of the QW holes and Co
$d$–shell orbitals is expected to scale like $\Delta E_{ex}(d_s) \sim \exp(-d_s/d_0)$
owing to wavefunction penetration through the rectangular
potential barrier. The same exponential behaviour holds for
the rate of hole tunnelling through the barrier, with a characteristic
barrier width $d_0 = \hbar/(2\Sigma m_s \Delta)$, which is less than 1 nm for a
heavy holes mass $m_h > 0.1 m_e$ and a barrier height $\Delta = 0.1 \text{ eV}$.
Thus, the possible coupling mechanism is ‘undeniably’ short-
ranged. At first sight, this is in agreement with the steep decrease
of PL intensity with decreasing barrier thickness owing to carrier
 tunnelling from the QW into the FM (the red squares Fig. 1f),
from which we can derive $d_s = 1.6 \text{ nm}$. However, the spin polarization
does not follow a similar steep decrease at all. The green circles
in Fig. 1f show that $\rho^\pi_s (d_s)$ at $B_F = B_{sat}$ seems to be slowly varying with $d_s$. Furthermore, and maybe even more surprising, the
proximity effect observed in our case is long-ranged and persists
over more than 30 nm, in contrast to our expectations based on
wavefunction overlap.

It should be noted that in systems other than the one studied
here a long-range proximity effect may occur, for example, due to
spin-dependent capture by the FM. Previously this effect has been
observed in a ferromagnetic GaMnAs/QW hybrid for electrons,
but not for holes\textsuperscript{19}. The tunnel capture rates $\gamma_+^s/\gamma_-$
of electrons with spin up (down) through the nonmagnetic spacer also have an
exponential dependence on spacer thickness. The non-equilibrium
polarization in the QW, however, is determined by the ratio $\gamma_+/\gamma_-$,
so that the exponential dependence cancels. In our case the spin-
dependent capture is weak in absolute terms, as it is related to
holes, and the proximity effect comes mainly from the $p$–$d$ exchange
interaction. Therefore we conclude that our results indicate a long-
range mechanism of $p$–$d$ exchange coupling.

**Origin of long-range $p$–$d$ exchange coupling**

In the following we discuss two possibilities for the observed long-
range coupling: magnetization of the holes by stray fields of the FM
film and spin polarization of holes by elliptically polarized phonons
near the FM/SC interface.

**Effect of FM stray magnetic fields on spin polarization of holes.**

It is known that the stray magnetic fields created in a SC by a nearby
FM (refs 15,16) have large penetration depths and induce dephasing
of the electron spin Larmor precession, characterized by the time
$\tau_{\text{ph}} = 1 \text{ ns}$ (Fig. 3d). The stray field averaged over a volume much
larger than the size of a magnetic domain is $4\pi M_d d_{sc}/L \sim 0.02 \text{ mT}$
for a Co film thickness of $d_{sc} = 5 \text{ nm}$ and a sample size of $L \approx 5 \text{ mm}$.
The hole spin polarization in a field of this strength is negligible.
Larger local stray fields $4\pi M_d d_{sc}/w$ appear on length scales comparable
with the domain size $w$. The stray field measured by
optical orientation is about 20 mT (see Supplementary Section A2)
and cannot provide a notable spin polarization. Therefore, stray
fields cannot explain the observed hole spin polarization.

**Spin polarization of holes by elliptically polarized phonons.**

The long-range $p$–$d$ exchange between FM and SC may be mediated
by elliptically polarized phonons generated in the ferromagnetic
layer. To the best of our knowledge, such effective $p$–$d$ exchange
coupling has not been discussed previously in the literature.
Subsequently we consider acoustic phonons as an example (coupling
with elliptically polarized optical phonon modes\textsuperscript{17} is discussed in
Supplementary Section D).

It is well established\textsuperscript{18–19} that transverse acoustic (TA) phonons
propagating through a FM along the magnetization direction
$\mathbf{m} = M/M_s$ (that is, phonon momentum $\mathbf{q} \parallel \mathbf{m}$) are elliptically
polarized. This polarization arises from the strong hybridization of
TA phonons (linear dispersion in momentum) and spin waves
(dispersion quadratic in momentum) near the crossing points

\begin{equation}
\rho^\pi_s = \frac{N_{s/2} - N_{-s/2}}{N_{s/2} + N_{-s/2}} \approx \frac{\Delta E_{ex}(M_s)}{2k_B T} \tag{1}
\end{equation}

Here $k_B$ is the Boltzmann constant, $\Delta E_{ex}(M_s)$ is the spin splitting
of the heavy holes in the FM exchange field, and $N_{s/2}$ ($N_{-s/2}$) is
the concentration of QW heavy holes with momentum projection
$+s/2$ ($-s/2$) onto the growth direction. We assume that $P(T) \ll 1$.
One can expect from equation (1) that the hole spin polarization
decreases with increasing $T$. The experiment confirms this trend
(Fig. 4a). An estimation for $T = 6 \text{ K}$ shows that 4% spin polarization
corresponds to a splitting $\Delta E_{ex}$ of about 50 µeV.
exchange coupling is mediated by elliptically online 109, DOI: 48, Ferromagnetic effect of a Mn delta layer in the GaAs barrier J. Appl. Phys. M | VOL 12 | JANUARY 2016 | Phys. Rev. B Introduction to Solid State Physics 3rd edn (Wiley, 1967). Phys. Rev. B µ
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11–64 (1988). exchange splitting is about ∆∥
(energy level cross the interface between a ferromagnet and a semiconductor, whereas the other one survives 20
2 nm), whereas the other one survives 19.

Recently20, it was found that TA phonons (shear waves) can easily cross the interface between a ferromagnet and a semiconductor, without an appreciable destructive effect. According to the continuity boundary conditions for displacement and stress, elliptically polarized modes will also propagate in the semiconductor. The elliptically polarized phonons transfer angular momentum from the FM into the SC and will interact with hole spins owing to the strong spin–orbit interaction in the valence band21. The effect obviously occurs over much larger spacer thicknesses than any mechanism based on wavefunction overlap because there is no energy barrier for phonons.

To get more insight, we assume a σ phon–magnon resonance. There are two such crossing points at frequencies of ω1 ≃ 1012 s⁻¹ and ω2 ≃ 1011 s⁻¹ (ℏων₁ < 1 meV), with two orthogonal phonon polarizations per crossing. Only the phonon mode with polarization vector rotating in the same direction as the magnetization vector in the spin wave participates in the coupling, whereas the other one couples only weakly to magnons. The coupled rotary phonon mode shows a strong damping (over a decay length ~ 2 nm), whereas the other one survives19.

Methods

Methods and any associated references are available in the online version of the paper.

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Figure 5 | Illustration of circularly polarized phonon mode in the FM–QW hybrid structure. Energy diagram: a circularly polarized σ phonon with energy ℏων > ∆ḥ couples the heavy-hole ground +3/2 state and the light-hole excited +1/2 state, inducing a spin-dependent shift of the hole spin levels—the ‘phonon a.c. Stark effect’.

Calculation of the ‘phonon a.c. Stark shift’ of the QW hole levels requires precise knowledge of many quantities, such as interaction parameters, phonon propagation directions, and so on. However, an estimation of the effective p–d exchange can be done relatively straightforwardly. Supplementary Equations (C3–C6) in Section C show that the p–d exchange splitting is about 50 μeV, leading to a PL polarization of 5%, in agreement with our experiment.

The ‘phonon a.c. Stark effect’—the spin-dependent shift of hole spin levels—will be stronger the closer the phonon energy ℏων > ∆ḥ is to the heavy–light-hole splitting ∆ḥ (energy level diagram in Fig. 5). Hence the splitting ∆Eexc should be larger for the acceptor-bound holes A with ∆ḥ ≈ 1 meV (ref. 23) than for the free QW holes with ∆ḥ ≈ 10 meV. Indeed, the proximity effect was detected at the e–A transition, but not at the X-transition.

The absence of FM-induced spin splitting for the QW electrons (and the related precession corresponding to the Larmor frequency) can then also be explained by the small spin–orbit interaction in the conduction band.

Therefore, we come to the following basic conjecture: the long-range p–d exchange coupling is mediated by elliptically polarized phonons. Implementation of techniques for exploitation of elliptically polarized phonons in semiconductors could have profound consequences for spin systems in general, and not only in hybrids. First, it could enable one to control the spin levels through the phonon analogue of the optical a.c. Stark effect22. Second, one may demonstrate phonon-assisted spin pumping: the absorption of circularly polarized phonons would create spin orientation of the holes in the valence band, similar to the well-known interband optical pumping in solids23 and gases25.
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**Author contributions**

V.L.K., M.S., I.A.A., V.F.S., L.L., I.V.K., J.D., R.I.D. and D.M. performed the experiments and analysed the data. V.L.K. developed the theoretical model. C.S. and H.H. performed AFM measurements. G.K., M.W. and T.W. fabricated the samples. V.L.K., I.A.A., D.R.Y., Yu.G.K, and M.B. co-wrote the paper. All authors discussed the results and commented on the manuscript.

**Additional information**

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at [www.nature.com/reprints](http://www.nature.com/reprints). Correspondence and requests for materials should be addressed to V.L.K. or I.A.A.

**Competing financial interests**

The authors declare no competing financial interests.
For magneto-optical Kerr effect (MOKE) measurements, we used a z◦ and 1∥ (I<−σ> |) in situ Mg−Te cap of the PL is defined as the degree of polarization. Circular or linear polarized excitation is indicated into a single grating spectrometer equipped with avalanche photodiode, or a double monochromator equipped with photomultiplier. The circular polarization degree of the PL is defined as ρc = (Ic − Iπ)/(Ic + Iπ), where Ic and Iπ are σ+ and σ− intensities of the PL. Circular or linear polarized excitation is indicated with exc=σ+ or π, respectively. For the proximity effect the measurements were performed under linearly polarized (exc=π) or unpolarized excitation. The circular polarization of the PL was measured with a photo-elastic modulator (PEM) in conjunction with a two-channel photon counting system. For optical orientation and Hanle effect measurements we used a circularly polarized excitation beam (exc=σ+). Here, a PEM was introduced in the excitation path, while one of the circular polarization components (σ+) was measured in the detection path. This allowed the suppression of effects related to dynamic nuclear polarization. The modulation parameter η = (I+ − I−)/(I+ + I−) was measured also with a PEM in the excitation path, whereas the total intensity was measured using a depolarization wedge in the detection path.

For TRPL measurements we used a mode-locked Ti–sapphire laser, emitting 1–2 ps at a 76 MHz rate. The laser beam was focused into a spot with a diameter of approximately 0.2 mm and the pulse fluences did not exceed 1 µJ cm−2. The degree of polarization was defined in the same way as in the cw experiments. However, no PEM was used here. The linear and circular polarization of optical excitation and detection were selected by rotating 1/2 and 1/4 plates, respectively, in conjunction with a Glan–Thompson prism. The emitted light was dispersed in a single grating spectrometer, equipped with a streak camera providing 20 ps time resolution. Time-integrated spectra were measured using a nitrogen-cooled charged coupled device which was connected to the same spectrometer.

The sign of the magnetic-field-induced circular polarization in the Faraday geometry was determined by comparing the sign of polarization in a diluted magnetic semiconductor (DMS) Cd1−xMnxTe/Cd1−xMnxTe QW structure for the same direction of magnetic field. In the DMS the sign of the circular polarization is positive (σ+) for B∥ > 0 (ref. 2). Measurements in hybrid structures show the opposite sign—that is, ρc < 0 for B∥ > 0.

Kerr rotation. For magneto-optical Kerr effect (MOKE) measurements, we used a Ti–sapphire laser. The magnetic field was applied along the growth axis c of the samples in the Faraday geometry for the polar MOKE and in the plane of the samples in the Voigt geometry for the longitudinal MOKE. The linearly polarized laser beam was focused on the sample into a spot with a diameter of approximately 0.3 mm and the power did not exceed 1 mW. The reflected beam was passed through a PEM in conjunction with a linear analyser and a photodetector (silicon photodiode). The main axis of the PEM is perpendicular to the initial polarization of the incident light, whereas the analyser axis is rotated by 45°. The rotation angle of the polarization is proportional to the measured signal, which is homodyne-detected at double the resonance frequency of the PEM (80 kHz) using a lock-in amplifier. In addition, MOKE signals were measured using a spectrally broad white-light source (tungsten lamp). In this way we confirmed that the Kerr signals originate from the Co film with a weak spectral dependence in the region of interest (700–800 nm).

Methods
Sample preparation. The semiconductor part of the structures was grown by molecular beam epitaxy in a commercial EPI-620 MBE system. The electrically heated effusion cells with PBN (pyrolytic boron nitride) crucibles loaded with commercially available 7N, Cd, Te and Zn ingots and a 5N Mg ingot served as sources of molecular fluxes. The growth of structures was performed at the standard growth temperature of 290 °C on commercial epi-ready (100)-GaAs substrates oriented 2◦ off towards (110). After oxide removal, 25 ML of ZnTe was grown to stabilize (100)-oriented growth of the few-micrometre-thick Cd1−yMgyTe buffer (y=0.2 as determined from the position of PL peak). The precise value of the growth rate was determined from the observed oscillations of the intensity of the specular spot of the reflection high energy electron diffraction (RHEED) pattern for each structure during the growth of the buffer layer. The anion-limited growth rate of CdTe and Cd1−yMgyTe was kept around 0.7 µm h−1 and the Cd/Te beam equivalent pressure (BE) was set to 1.1 (found to be the optimal for the growth of CdTe). After the growth of the CdTe QW and Cd1−yMgyTe cap, the structures were cooled down and transferred (through an ultrahigh vacuum transfer chamber) to the second MBE chamber (PREVAC) for the deposition of the Co layer. The source of the Co flux was a 4N Co rod heated by an electron beam (inside the four-pocket mini e-beam evaporator). During the deposition of Co the structure was kept at room temperature to prevent interdiffusion. The deposition rate of Co was predetermined in a separate calibration run and controlled in situ by means of a quartz rate monitor. Varying thicknesses of either the Cd1−yMgyTe cap or Co layer were produced by the time-controlled linear movement of the main shutters in each of the two MBE chambers.

Optical experiments. The samples were placed in the variable temperature insert of an optical liquid-helium cryostat equipped with superconducting split-coils or an external electromagnet. The experiments were performed in a backscattering geometry with excitation and detection directions being perpendicular to the sample plane (parallel to the growth direction axis x). Magnetic fields up to 3 T were applied in Voigt (B∥ |x) or Faraday (B∥ |z) geometries. For oblique field measurements we used two electromagnets where the excitation densities did not exceed 100 W cm−2.

For continuous wave (cw) photoluminescence (PL) experiments. However, no PEM was used here. The linear and circular polarization of optical excitation and detection were selected by rotating 1/2 and 1/4 plates, respectively, in conjunction with a Glan–Thompson prism. The emitted light was dispersed in a single grating spectrometer, equipped with a streak camera providing 20 ps time resolution. Time-integrated spectra were measured using a nitrogen-cooled charged coupled device which was connected to the same spectrometer.

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Kerr rotation. For magneto-optical Kerr effect (MOKE) measurements, we used a Ti–sapphire laser. The magnetic field was applied along the growth axis c of the samples in the Faraday geometry for the polar MOKE and in the plane of the samples in the Voigt geometry for the longitudinal MOKE. The linearly polarized laser beam was focused on the sample into a spot with a diameter of approximately 0.3 mm and the power did not exceed 1 mW. The reflected beam was passed through a PEM in conjunction with a linear analyser and a photodetector (silicon photodiode). The main axis of the PEM is perpendicular to the initial polarization of the incident light, whereas the analyser axis is rotated by 45°. The rotation angle of the polarization is proportional to the measured signal, which is homodyne-detected at double the resonance frequency of the PEM (80 kHz) using a lock-in amplifier. In addition, MOKE signals were measured using a spectrally broad white-light source (tungsten lamp). In this way we confirmed that the Kerr signals originate from the Co film with a weak spectral dependence in the region of interest (700–800 nm).