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Quenching of magnetization in (III, Mn)V magnetic semiconductor quantum wells under intense laser field assisted by the quasi-two-dimensional electron gas

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ABSTRACT

Laser-induced quenching of ferromagnetism in $(III_{1-x}, Mn_x)V$ quantum well magnetic semiconductor is investigated. We propose a mechanism in which an increase of the magnon population of the ferromagnetic sample can be achieved due to the spin-flip electron–magnon scattering of the quasi-two-dimensional electron gas inside the quantum well magnetic semiconductor in the presence of intense laser field. In this case, the laser field imposes a drift velocity to the quasi-two-dimensional electrons so that whenever this drift velocity exceeds the phase velocity of the spin waves, energy from the quasi-two-dimensional electrons gained at the expense of the laser field is transferred to the magnon system thereby increasing the number of magnons (magnon amplification) and as a consequence, a loss of magnetization is obtained. Application for typical $(III_{1-x}, Mn_x)V$ ferromagnetic semiconductor quantum wells such as $Ga_{1-x}Mn_xAs/AlAs$ ($x \sim 5\%$) provides a reasonable loss of magnetization up to 30 % for laser electric field strengths up to 4×10^5 V/cm which is below sample damage threshold field values.

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1. Introduction

Diluted magnetic semiconductors (DMS's) based on III–V semiconductors doped with Mn have attracted a lot of interest recently, after critical temperatures for the onset of ferromagnetism of the order of 110 K have been found in $Ga_{1-x}Mn_xAs$, where $x = 0.053$ [1–4]. More recently, critical temperatures larger than room temperatures have been reported in Mn-doped GaN, enhancing the hope for extensive technological applications of these materials [5]. Unlike in ferromagnetic metals, there is a clear distinction between mobile carriers and localized spins (Mn ions), and ferromagnetic order is realized through their strong coupling (p–d exchange interaction). This coupling in turn makes magnetic order sensitive to changes in carrier density of the ferromagnetic sample via external perturbations [6–9], e.g. intense laser irradiation [10,11]. Pumping a magnetic system with ultrashort laser pulses the equilibrium among the constituents (carrier, magnetic spins and the lattice) can be strongly altered, triggering a variety of dynamical processes. Studying these processes can provide estimates for the timescales and strengths of the various interactions. In fact, it has been recently reported [12] that spin-flip one magnon–electron scattering in $(III_{1-x}, Mn_x)V$ quantum wells is an ultrafast interaction process which occurs with timescale of order 1 ps. The spectrum and nature of the spin waves of a (III, Mn)V diluted magnetic semiconductor has been reported by some authors [13,14]. On the other hand, the discovery of ultrafast demagnetization [15,16] produced by such ultrashort laser pulses suggested an ultrafast scheme for magneto-optical data writing. The knowledge of how a laser field can effectively change the magnetic moment of the sample is still a matter of debate [17–19] and it is of main interest from technological viewpoints [20].

One possible mechanism for quenching ferromagnetism and the one we propose to investigate here in the current paper, is the mechanism in which an increase of the magnon population of the ferromagnetic sample is achieved due to the spin-flip electron–magnon scattering of the quasi-two-dimensional electron gas inside a $(III_{1-x}, Mn_x)V$ quantum well magnetic semiconductor in the presence of an intense laser field. In this case, as we shall see below, the laser field imposes a drift velocity to the quasi-two-dimensional electrons so that whenever this drift velocity exceeds the phase velocity of the spin waves, energy from electrons gained at the expense of the laser field is transferred to the magnon system thereby increasing the number of magnons (magnon amplification) and as a consequence, a loss of magnetization is obtained.

The problem of the interaction of intense laser fields with magnetic semiconductors (e.g. EuO) has been discussed on several occasions [10,11]. In particular, it has been shown that, under the influence of the strong radiation field, the magnon damping in a ferromagnetic semiconductor may change considerably in magnitude and even in signal (amplification). This mechanism

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involves quanta of the external field and it is important in the study of non-equilibrium states of the magnon subsystem since the magnon deviation from equilibrium is, in this case, due to the energy transfer from electrons to magnons after absorption of quanta of the external field. The presence of extra magnons into the sample channeled by the electrons giving up their energy acquired from the external field makes the magnetization of the sample relative to the saturation level decreases. Therefore, since most of the magneto-optical data writing devices depends strongly on the amount of magnetization of the sample we believe our study is of importance both from scientific and technological viewpoints.

The physical picture we propose here can be understood as follows. From the macroscopic standpoint a ferromagnet may be looked upon as a continuous medium characterized by a magnetic moment density (magnetization) $\vec{M}(\vec{r})$. One can show that for weak oscillation of $\vec{M}(\vec{r})$ about its equilibrium direction, say the z-direction, the value of its z-component, M_z, can be expressed in terms of magnon creation and annihilation operators $b^{\dagger}_{\vec{q}}$ and $b_{\vec{q}}$, as [21].

$$M_z = M_0 - \frac{\mu}{V}\sum_{\vec{q}}\left\langle N_{\vec{q}}\right\rangle, \tag{1}$$

where $N_{\vec{q}} = b^{\dagger}_{\vec{q}} b_{\vec{q}}$, M_0 is the magnetization of the whole sample if there are no magnons in it, M_z is the magnetization of the sample when magnons are present, V is the crystal volume and $\sum_{\vec{q}}\left\langle N_{\vec{q}}\right\rangle$ is the total number of ferromagnons each of which reduces the sample's magnetic moment by μ. Here $\langle\cdots\rangle$ means statistical average. It then follows that if one excites spin waves by some external action (laser) to the extent of causing amplification (growth) of the magnon population, the magnetization of the sample relative to the saturation level will decrease.

In order to substantiate the above physical picture and to get the size of the demagnetization effect we need to evaluate the amplified magnon population due to the action of the intense laser field. To be more specific, we have considered the interaction of the quasi-two-dimensional electrons with localized Mn spins (the density of Mn spins participating in ferromagnetic order is 10^{21} cm^{-3}) in a Ga_{1-x} Mn_xAs (33 nm)/AlAs (820 nm) heterostructure with Curie temperature of the order of 110 K in the presence of an intense laser field of frequency ω. We shall then calculate firstly, the matrix elements of electron–magnon scattering, then give the rate of change of the magnon population and the estimate the threshold value of the field strength for magnon amplification. The change in the magnetization in the magnetic semiconductor heterostructure is finally calculate by making use of Eq. (1).

2. Formalism

Let there be the electromagnetic plane wave propagating normal to the interface and penetrating well into the sample. Suppose that its wavelength is far great than both the men free path of the electrons and the width of the interfacial potential well so that the spatial dependence of the laser wave can be neglected. This assumption is not essential, but can simplify the mathematical treatment considerably.

To calculate the matrix elements for electron–magnon scattering, we solve the *Schrödinger* equation for the electron wave function $\Psi(\vec{r}, t)$,

$$i\hbar\frac{\partial}{\partial t}\Psi_{\sigma}(\vec{r}, t) = \frac{1}{2m}\left(\vec{p}_{-}\frac{e}{c}\vec{A}(t)\right)^2\Psi_{\sigma}(\vec{r}, t) + V(z)\Psi_{\sigma}(\vec{r}, t) \tag{2}$$

where the vector potential $\vec{A}(t)$ can be expressed as

$$\vec{A} = A_0\vec{e}_{\parallel}\cos\omega t, \tag{3}$$

and where the scalar potential $V(z)$, which represents the potential in the direction perpendicular to the interface, is given as

$$V(z) = \begin{cases} 0, & 0 < z < D \\ \infty, & 0 > z,\ z > D. \end{cases} \tag{4}$$

Here, $\vec{e}_{\parallel}$ is the unit vector parallel to the interface, m is the electron effective mass, D is the width of the interfacial potential well and $\sigma = -1(+1)$ for spin-up (-down) electron subband in the magnetic semiconductor heterostructure. The solution of Eq. (2) is

$$|\vec{k}_{\parallel}, l, \sigma\rangle = \Psi_{\vec{k}_{\parallel},l,\sigma}(\vec{r}, t) = \left\{\frac{2}{DA}\right\}^{1/2}\sin\left(\frac{\pi l}{D}z\right)\exp\left\{i\vec{k}_{\parallel}\cdot\vec{r}_{\parallel}\right.$$
$$\left. -\frac{i}{\hbar}\int_0^t\left[E_0 l^2 + \frac{1}{2}\sigma\hbar\omega_s + \frac{1}{2}\left(\hbar\vec{k}_{\parallel} - \frac{e}{c}\vec{A}(\tau)\right)^2\mathrm{d}\tau\right]\right\}, \tag{5}$$

where $E_0 = \frac{\hbar^2}{2m}\left(\frac{\pi}{D}\right)^2$, $\omega_s = N_0\alpha S x/\hbar$, is the spin-splitting frequency between spin subbands of the magnetic semiconductor quantum well, $N_0\alpha$ is the spin-flip electron–magnon interaction strength, N_0 being the density of Mn spins, S is the Mn spin ($S = 5/2$) and x is the molar fraction of Mn spins in the magnetic quantum well. Here $\vec{k}_{\parallel}$ is the component of the electron wave vector parallel to the interface, l ($l = 1, 2, 3\ldots$) are the quantum numbers describing the electron motion perpendicular to the interface, and the area A accounts for the normalization of this wave function.

As for the localized spin system [12] the field operator of the magnons can be written as

$$\phi(\vec{q}, \omega_{\vec{q}}; \vec{r}, t) = C\mathrm{e}^{(i\vec{q}\cdot\vec{r} - i\omega_{\vec{q}}t)} \tag{6}$$

where $\vec{q} = \left(\vec{q}_{\parallel}, q_z\right)$ is the magnon wave vector, $\omega_{\vec{q}}$ is the magnon frequency, and

$$C = \left(\frac{S}{2N_c}\right)^{1/2} N_0\alpha x, \tag{7}$$

N_c being the number of cation sites. Here, $\vec{q}_{\parallel} = \left(q_x, q_y\right)$.

As we know, in bulk magnetic materials, spin waves are free to travel in all three dimensions resulting in a continuous dispersion of the spin wave energy $\hbar\omega_{\vec{q}}$ with the three-dimensional momentum q. If one restricts one of the dimensions (say the z direction) going to the thin film (at nanometer scale) geometry, due to the confinement of the two boundaries (interfaces), spin waves are scattered back and forth between the boundaries. If the film thickness equals the integral multiple of the half wavelength projected along z, standing waves are formed [22]. Such standing spin waves can be regarded as oscillations of the magnetization which are nonuniform in the direction normal to the surface and which travel freely in the two other dimensions. Therefore, the dispersion relation is given by a series of spin wave branches quantized in the momentum perpendicular to the plane q_z and continuous in the momenta in the plane q_x and q_y. For the sake of simplicity we disregard the effect of magnon confinement and a continuous dispersion of the spin wave energy $\hbar\omega_{\vec{q}}$ with the three-dimensional momentum q is assumed.

Treating the electron–magnon interaction as a perturbation, the transition matrix elements between the initial state $|\vec{k}_{\parallel}, l, \sigma\rangle$ and the final state $|\vec{k}'_{\parallel}, l', \sigma'\rangle$ accompanied by the emission of magnons is

$$a(\vec{k}'_{\parallel}, l', \sigma' \to \vec{k}_{\parallel}, l, \sigma) = -\frac{i}{\hbar}\int \mathrm{d}^2\vec{r}_{\parallel}\int \mathrm{d}z\int \mathrm{d}t$$
$$\times\left\langle\vec{k}'_{\parallel}, l', \sigma'\left|\phi(\vec{q}, \omega_{\vec{q}}; \vec{r}, t)\right|\vec{k}_{\parallel}, l, \sigma\right\rangle. \tag{8}$$

By substituting Eqs. (5) and (6) into Eq. (8) and using the formula of Bessel-function expansion, we get

$$\exp\left[-ix\sin(\omega t)\right] = \sum_{n=-\infty}^{+\infty} J_n(x)\exp(-in\omega t). \tag{9}$$

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