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A M Kadigrobov[1,2,7]**, R I Shekhter**[1]**, S I Kulinich**[1,3]**, M Jonson**[1,4,5]**,
O P Balkashin**[3]**, V V Fisun**[3]**, Yu G Naidyuk**[3]**, I K Yanson**[3]**,
S Andersson**[6] **and V Korenivski**[6]

[1] Department of Physics, University of Gothenburg, SE-412 96 Göteborg, Sweden

[2] Theoretische Physik III, Ruhr-Universität Bochum, D-44801 Bochum, Germany

[3] B I Verkin Institute for Low Temperature Physics and Engineering, 47 Lenin Avenue, 61103 Kharkov, Ukraine

[4] SUPA, Department of Physics, Heriot-Watt University, Edinburgh EH14 4AS, UK

[5] Division of Quantum Phases and Devices, School of Physics, Konkuk University, Seoul 143-701, Korea

[6] Nanostructure Physics, Royal Institute of Technology, SE-106 91 Stockholm, Sweden

E-mail: anatoli.kadygrobov@physics.gu.se

Abstract. We propose to use a point contact between a ferromagnetic and a normal metal in the presence of a magnetic field for creating a large inverted spin population of hot electrons in the contact core. The key point of the proposal is that when these hot electrons relax by flipping their spin, microwave photons are emitted, with a frequency tunable by the applied magnetic field. While point contacts are an established technology, their use as a photon source is a new and potentially very useful application. We show that this photon emission process can be detected by means of transport spectroscopy and demonstrate stimulated emission of radiation in the 10–100 GHz range for a model point contact system using a minority-spin ferromagnetic injector. These results can potentially lead to new types of lasers based on spin injection in metals.

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[7] Author to whom any correspondence should be addressed.

Contents

1. Introduction

Point contact spectroscopy detects the relaxation of hot electrons in a small region of a large sample and is a well-known method for studying elementary excitations in metals [1]. By using this method, the spectral properties of e.g. phonons and magnons can be extracted from the bias-voltage dependence of the current flowing through the point contact and, in particular, its component due to the inelastic backscattering of electrons in collisions involving large momentum transfers.

Whether the point contact geometry can be used to make a metal-based laser[8] is an interesting question that we explore in this paper. For this to be possible, it is necessary to show that photons can be emitted as a continuous flow of hot electrons relax in the contact region and, specifically, that stimulated photon emission leads to a greatly enhanced radiation intensity. This is what we will do in what follows.

Point contact spectroscopy cannot be applied for studying electron–photon interactions directly, since the momentum of photons is very small. However, by using a point contact between a ferromagnet and a normal metal (or between two ferromagnets) the electron spin comes into play through spin-polarized injection [3]–[9]. The spin-split energy bands of the injected electrons can lead to the emission of photons when the electrons undergo spin-flip relaxation, essentially with no change in the momentum. Since the resistance of the spin-up and spin-down channels in magnetic point contacts is different, both the emission and absorption of photons caused by spin-flip inter-channel transitions affect the total current through the contact and is therefore detectable by transport spectroscopy.

Below we show that a voltage-biased point contact between a ferromagnet and a normal metal can be used for generating photons with a frequency that can be tuned by means of an external magnetic field through the Zeeman splitting of the spin-up and spin-down energy subbands on the normal metal side of the contact. We show additionally that for realistic magnetic point contacts the spin-flip radiation produced can be detected by means of conventional point contact spectroscopy.

We will first present our model and start with the formalism used for analyzing the transport through the model point contact shown in figure 1. The relative weakness of the electron–photon interaction allows us to proceed in two steps. In the first step we calculate the spin populations for electrons in the contact region, to zeroth order in the electron–photon interaction strength.

[8] Electromagnetic radiation from a planar contact between a ferromagnetic and a non-magnetic semiconductor in an external magnetic field was detected by Viglin *et al* [2].
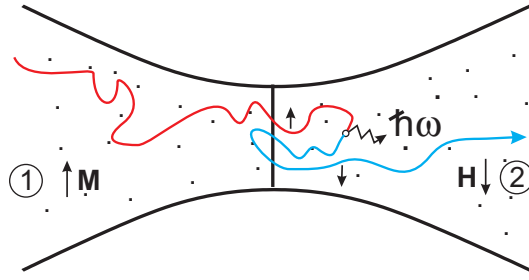
Figure 1. Diffusive point contact under irradiation (not shown) in the presence of a static magnetic field H. A voltage bias V injects a spin-polarized current from a ferromagnetic metal (1) with magnetic moment M into a normal metal (2). An electron with its magnetic moment up (spin-down) is shown to move along a diffusive trajectory from metal 1 to metal 2 (red line) where it resonantly interacts with the irradiation field, which results in a spin flip and the emission of a photon. The electron continues along its diffusive path with the magnetic moment down (blue line), thereby changing the spin-dependent contact resistance.

In the second step we find the photocurrent in the presence of radiation as well as the resulting change in point contact resistance, to first order in the electron–photon interaction.

2. Formalism

In order to calculate the electrical current and the spin accumulation, one needs to find the electron distribution function $f_{\sigma p}^{(s)}$ on either side of the contact, i.e. in the ferromagnet ($s = 1$) and in the normal metal ($s = 2$), for both spin projections $\sigma/2$ ($\sigma = \pm 1$) as a function of position $\boldsymbol{r}$ and electron momentum $\boldsymbol{p}$. In each of the metals these functions satisfy the Boltzmann equation

$$\boldsymbol{v}_\sigma^{(s)} \frac{\partial f_{\sigma p}^{(s)}}{\partial \boldsymbol{r}} - e \frac{\partial \Phi^{(s)}}{\partial \boldsymbol{r}} \frac{\partial f_{\sigma p}^{(s)}}{\partial \boldsymbol{p}} + \frac{f_{\sigma p}^{(s)} - \langle f_{\sigma p}^{(s)} \rangle}{\tau_\sigma^{(s)}} = \sigma w_{\mathrm{ph}}^{(s)}\{f_{\uparrow p}^{(s)}, f_{\downarrow p}^{(s)}\}, \quad s = 1, 2. \tag{1}$$

Here $\boldsymbol{v}_\sigma^{(s)}$ is the electron velocity in each metal, which is given by a momentum derivative of the electron energy as $\boldsymbol{v}_\sigma^{(s)} = \partial E_\sigma^{(s)}(\boldsymbol{p})/\partial \boldsymbol{p}$, where $E_\sigma^{(1)}(\boldsymbol{p}) = \varepsilon^{(1)}(\boldsymbol{p}) - \sigma J_1$ and $E_\sigma^{(2)}(\boldsymbol{p}) = \varepsilon^{(2)}(\boldsymbol{p}) + \sigma \mu_{\mathrm{B}} H$ both contain a spin-independent kinetic energy term $\varepsilon^{(s)}(\boldsymbol{p})$. For convenience of notation, $\sigma = +1$ and -1 here and below correspond to the directions of the electron magnetic moment parallel and antiparallel to the magnetization direction in the ferromagnet ($s = 1$), respectively (that is, the electron magnetic moment projections in the ferromagnet are $m_\sigma^{(1)} = \mu_{\mathrm{B}} \sigma/2$). The spin dependence of the energy in the normal metal ($s = 2$) is due to a static external magnetic field H and the associated Zeeman energy gap $2\mu_{\mathrm{B}} H$ (here and below we assume that the electron g-factor $g = 2$), while the much stronger spin dependence in the ferromagnetic metal ($s = 1$) is due to the exchange energy J_1 (the Zeeman energy can be neglected here). Furthermore, $\tau_\sigma^{(s)} = l_0/|\boldsymbol{v}_\sigma^{(s)}|$ is the elastic relaxation time, l_0 is the elastic mean free path of the electrons in the diffusive transport regime considered in this paper, $\Phi^{(s)}$ is the electric potential in the respective metal and the notation $\langle \ldots \rangle$ implies an average of the bracketed quantity over the Fermi surface.

The amplitude of the electromagnetic field irradiating the point contact is assumed to be large enough to allow the electron–photon interaction to be treated semi-classically, so that the collision integral in equation (1) can be written as

$$w_{ph}^{(s)}\{f_{\uparrow p}^{(s)}, f_{\downarrow p}^{(s)}\} = \frac{2\pi}{\hbar}|\mu_{\rm B} h_{ac}|^2 \left[f_{\downarrow p-q}^{(s)} - f_{\uparrow p}^{(s)} \right] \delta(E_{\uparrow}^{(s)}(\boldsymbol{p}) - E_{\downarrow}^{(s)}(\boldsymbol{p} - \boldsymbol{q}) - \hbar\omega). \tag{2}$$

Here h_{ac} is the magnetic amplitude of the electromagnetic wave of frequency ω and momentum $|\boldsymbol{q}| = \hbar\omega/c$ that irradiates the point contact and c is the velocity of light.

To facilitate explicit calculations we will consider a simplified contact geometry, approximating the point contact by a cylindrical channel of length L and diameter d, with $L \gg d \gg l_0$. The boundary conditions for the electron distribution functions $f_{\sigma p}^{(s)}$ at the interface between metals 1 and 2 can be written in the form

$$\begin{aligned}
f_{\sigma p}^{(1)} &= (1 - D_\sigma) f_{\sigma p_{\rm R}}^{(1)} + D_\sigma f_{\sigma p_{\rm T}}^{(2)}, \\
f_{\sigma p}^{(2)} &= D_\sigma f_{\sigma p_{\rm T}}^{(1)} + (1 - D_\sigma) f_{\sigma p_{\rm R}}^{(2)},
\end{aligned} \tag{3}$$

where $D_\sigma = D_\sigma(\boldsymbol{p}, \boldsymbol{p}_{\rm T})$ is the spin-dependent transparency of the interface; $\boldsymbol{p} = (\boldsymbol{p}_\parallel, p_z)$ and $\boldsymbol{p}_{\rm R} = (\boldsymbol{p}_\parallel, -p_z)$ (here $\boldsymbol{p}_\parallel = (p_x, p_y)$) are the momenta of the incident and reflected electrons, respectively; the momentum of the transmitted electron $\boldsymbol{p}_{\rm T}$ is determined by the condition of energy conservation $E_\sigma^{1,2}(\boldsymbol{p}) = E_\sigma^{2,1}(\boldsymbol{p}_{\rm T})$.

Away from the contact region, the current spreads over a large volume so that its density decreases and the electron system is essentially in equilibrium at distances $|\boldsymbol{r}| \gg d$. In our simplified geometry, we will therefore use the additional boundary conditions $f_{\sigma p}^{(1,2)}(z = \pm L/2) = n_{\rm F}(E_\sigma^{(1,2)}(\boldsymbol{p}))$, where $n_{\rm F}$ is the Fermi distribution function and the z-axis is directed along the point contact.

We will now solve the electron–photon scattering problem formulated above in the weak scattering limit characterized by $d/l_{\rm ph} \ll 1$, where $l_{\rm ph}$ is the electron–photon scattering length. This allows us to solve the Boltzmann equations (1) by perturbation theory, where $w_{\rm ph}^{(s)}$, $f_{\sigma p}^{(s)}$ and $\Phi^{(s)}$ are expanded in powers of the small parameter $d/l_{\rm ph}$. We will first solve the problem to zeroth order in $d/l_{\rm ph}$, which allows us to find the density of hot electrons with an inverse spin population in the contact region and then solve for the photocurrent to first (linear) order in $d/l_{\rm ph}$.

3. Spin accumulation

To solve the kinetic equations (1) to zeroth order in $d/l_{\rm ph}$, we generalize the procedure developed in [10]–[12] to allow for spin-dependent electron dynamics. To zeroth order, the distribution functions $f_{\sigma p}^{(s)}$ can be written as

$$f_{\sigma p}^{(s)} = \alpha_{\sigma p}^{(s)} n_{\rm F}\left(E_\sigma^{(s)}(\boldsymbol{p}) + e\phi_0(\boldsymbol{r}) - eV/2\right) + (1 - \alpha_{\sigma p}^{(s)})n_{\rm F}\left(E_\sigma^{(s)}(\boldsymbol{p}) + e\phi_0(\boldsymbol{r}) + eV/2\right), \tag{4}$$

where $\alpha_{\sigma p}^{(s)}(\boldsymbol{r})$ is the probability that an electron emanating from far inside the ferromagnet ($z = -\infty$) diffuses elastically to reach the point $\boldsymbol{r}$ in the metal s with the momentum $\boldsymbol{p}$; the concrete form of the electrical potential $\phi_0(\boldsymbol{r})$ inside the point contact is not important in the limit $eV \ll \varepsilon_{\rm F}$. The distribution functions $f_{\sigma p}^{(2)}$ are sketched in figure 2.
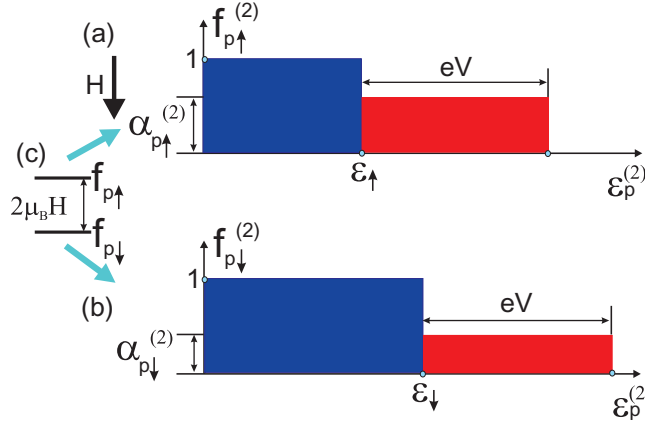
Figure 2. Zero-temperature energy distributions for (a) magnetic moment-up (spin-down), $f_{p\uparrow}$, and (b) magnetic moment-down (spin-up) electrons, $f_{p\downarrow}$, at point r on the normal-metal side of the point contact. The inset (c) shows the Zeeman energy splitting and the direction of the magnetic field H. All states are occupied up to $\varepsilon_\uparrow = \varepsilon_f - eV/2 - \mu_B H$ and $\varepsilon_\downarrow = \varepsilon_f - eV/2 + \mu_B H$, respectively (blue rectangles), but in the intervals $(\varepsilon_\uparrow, \varepsilon_\uparrow + eV)$ and $(\varepsilon_\downarrow, \varepsilon_\downarrow + eV)$ the states are only partly occupied (red rectangles) and to an extent that is determined by the probabilities $\alpha_{\uparrow p}(r)$ and $\alpha_{\downarrow p}(r)$ for 'hot' electrons in the ferromagnet to reach r. Clearly, the difference between the densities of spin-down and spin-up electrons, $n_\uparrow(r) - n_\downarrow(r) \propto [(\alpha_\uparrow^{(2)} - \alpha_\downarrow^{(2)})eV - 2\mu_B H]$, depends on the bias voltage V. It follows that the spin population can be inverted, so that $n_\uparrow(r) > n_\downarrow(r)$, for large enough V if $\alpha_\uparrow^{(2)} > \alpha_\downarrow^{(2)}$.

To linear order in the parameter $l_0/d \ll 1$, it follows from equations (1) and (3) that this probability can be expressed as $\alpha_{\sigma p}^{(s)} = \langle \alpha_{\sigma p}^{(s)} \rangle - l_0(v_z/|\boldsymbol{v}|)\mathrm{d}\langle \alpha_{\sigma p}^{(s)} \rangle/\mathrm{d}z$. The isotropic part of $\alpha_{\sigma p}^{(s)}$ satisfies the diffusion equation

$$\frac{\mathrm{d}^2}{\mathrm{d}z^2}\langle \alpha_{\sigma p}^{(s)} \rangle = 0, \tag{5}$$

with the boundary conditions $\langle \alpha_{\sigma p}^{(1)}(z = -L/2) \rangle = 1$ and $\langle \alpha_{\sigma p}^{(2)}(z = L/2) \rangle = 0$; in the vicinity of the F/N interface the effective boundary conditions are [11]

$$\begin{aligned}
\langle \alpha_{\sigma p}^{(2)} \rangle - \langle \alpha_{\sigma p}^{(1)} \rangle &= \frac{l_0}{\langle D_\sigma \rangle}\frac{\mathrm{d}\langle \alpha_{\sigma p}^{(1)} \rangle}{\mathrm{d}z}, \\
\frac{\mathrm{d}\langle \alpha_{\sigma p}^{(1)} \rangle}{\mathrm{d}z} &= \frac{\mathrm{d}\langle \alpha_{\sigma p}^{(2)} \rangle}{\mathrm{d}z},
\end{aligned} \tag{6}$$

if the transparency of the interface is assumed to be small, $\langle D_\sigma \rangle \ll 1$. Solving the diffusion equation (5) with these boundary conditions, one finds that

$$\langle \alpha_\sigma^{(1)} \rangle = 1 - \beta_\sigma^{(1)}\left(1 + \frac{2z}{L}\right), \quad \langle \alpha_\sigma^{(2)} \rangle = \beta_\sigma^{(2)}\left(1 - \frac{2z}{L}\right), \tag{7}$$

where

$$\beta_\sigma^{(s)} = \frac{\kappa_\sigma^{(s)}}{1 + \kappa_\sigma^{(1)} + \kappa_\sigma^{(2)}}, \quad \kappa_\sigma^{(s)} = \langle D_\sigma \rangle\frac{L}{2l_0}. \tag{8}$$

If electrons are injected from the ferromagnet (1) into the normal metal (2) (i.e. if $eV > 0$) the number of 'hot' electrons with spin up ↑ and down ↓ that accumulate in the effective volume $\Omega_{\mathrm{PC}}^{(2)} \sim d^3$ of the normal metal in the point contact (PC) is

$$\delta n_\sigma = \int_{\Omega_{\mathrm{PC}}^{(2)}} \mathrm{d}^3 r \int \frac{\mathrm{d}^3 p}{(2\pi\hbar)^3} \left[f_{p\sigma}^{(2)}(r) - n_{\mathrm{F}} \left(E_\sigma^{(2)}(p) + e\phi_0(r) + eV/2 \right) \right].$$

Using equations (4), (7) and (8) this expression can be evaluated to give

$$\delta n_\sigma = \frac{\beta_\sigma^{(2)}}{2} \left(n_0 \Omega_{\mathrm{PC}}^{(2)} \right) \frac{eV}{\varepsilon_{\mathrm{F}}}, \tag{9}$$

where n_0 is the conduction electron density in the normal metal.

From the result (9) we conclude that the total number of hot electrons injected into the normal-metal side of the contact is

$$\delta n = \gamma_{\mathrm{tr}} \left(n_0 \Omega_{\mathrm{PC}}^{(2)} \right) \frac{eV}{\varepsilon_{\mathrm{F}}}, \quad \gamma_{\mathrm{tr}} = \frac{\beta_\uparrow^{(2)} + \beta_\downarrow^{(2)}}{2} \tag{10}$$

and the induced magnetic moment corresponding to the net spin density accumulated in the same region is

$$\delta M = \mu_{\mathrm{B}} S \delta n = \mu_{\mathrm{B}} \beta_{\mathrm{tr}} \left(n_0 \Omega_{\mathrm{PC}}^{(2)} \right) \frac{eV}{2\varepsilon_{\mathrm{F}}}. \tag{11}$$

Here S, the effective spin of an injected electron, is

$$S = \frac{1}{2} \frac{\delta n_\uparrow - \delta n_\downarrow}{\delta n} = \frac{1}{2} \frac{\beta_\uparrow^{(2)} - \beta_\downarrow^{(2)}}{\beta_\uparrow^{(2)} + \beta_\downarrow^{(2)}} \equiv \frac{1}{2} \beta_{\mathrm{tr}} \tag{12}$$

and β_{tr} is a measure of the spin polarization of the hot electrons injected into the contact region. If the size d of the contact is a few tens of nm and $\beta_{\mathrm{tr}} \sim 0.3$, which corresponds to a nearly ballistic point contact with $d \sim l_0$ and a spin polarization of 30% at the F/N interface, the injected number of hot electrons and the induced magnetic moment in the contact region are $\delta n \sim 10^6 \, eV/\varepsilon_{\mathrm{F}}$ and $\delta M \sim 10^6 \mu_{\mathrm{B}} \, eV/\varepsilon_{\mathrm{F}}$, respectively.

4. Photocurrent

The previous calculations can readily be extended to find the photocurrent flowing through the point contact under irradiation. Since the electron–photon interaction hardly affects the electron momentum at all, the main cause of the photocurrent is the photon-induced electron spin-flip transitions in conjunction with the spin dependence of the contact resistance. The spin flips change the electron spin densities in the contact and the spin-dependent contact resistance is connected with the different densities of states for the two spin projections.

To find the photocurrent, we first solve the Boltzmann equation (1) for the photon-induced change $f_{\sigma p,1}^{(s)}(r)$ in the electron distribution function. We do so to lowest (linear) order in the small parameter d/l_{ph} and with the boundary conditions $f_{\sigma p,1}^{(1,2)}(z = \mp L/2) = 0$. The matching conditions at the F/N interface are given by equation (3) with the change $f_{\sigma p}^{(s)} \to f_{\sigma p,1}^{(s)}$. Using these solutions, one finds the photocurrent as

$$I_{\mathrm{ph}} = e \sum_{s=1,2} \int_{\Omega_{\mathrm{PC}}^{(s)}} \mathrm{d}r \int \frac{\mathrm{d}p}{(2\pi\hbar)^3} \left(\alpha_{\uparrow,-p}^{(s)}(r) - \alpha_{\downarrow,-p}^{(s)}(r) \right) w_{\mathrm{ph}}^{(s)} \{ f_{\uparrow p0}^{(s)}, f_{\downarrow p0}^{(s)} \}. \tag{13}$$

Using equations (13), (7) and (8), one obtains the total current $I(V)$ in a diffusive point contact under irradiation as

$$I(V) = \frac{V}{R} + \theta \left(1 - \frac{|\hbar\omega - 2\mu_B H|}{\hbar\omega} \frac{c}{v_F} \right) j_{ph}(V),$$

$$j_{ph}(V) = \frac{\Delta R}{R^2}(V - V^*). \tag{14}$$

Here R is the 'dark' contact resistance due mainly to the impurities, while the relative change of the point contact resistance caused by the irradiation is

$$\frac{\Delta R}{R} = \frac{(2\pi\bar{\beta}_{tr})^2}{6} \frac{c}{v_F} \frac{|\mu_B h_{ac}|^2}{\varepsilon_F \hbar\omega} (n_0 \Omega_{PC}^{(2)}) \left(\frac{2e^2}{h} R \right), \tag{15}$$

where $\bar{\beta}_{tr} = \beta_{tr}\gamma_{tr}$ and $eV^* = (3/4)\hbar\omega/\bar{\beta}_{tr}$. As one sees from equation (14), the dependence of the photocurrent on the magnetic field has a peak corresponding to the resonant interaction of the electron spin and the electromagnetic field.

A comparison between equation (13) and the rate equation for photons generated by electronic spin-flip transitions induced by the electromagnetic field (see [7]),

$$\frac{dn_{ph}^{(s)}}{dt} = -\int w_{ph}^{(s)} \{f_{\uparrow,p}^{(s)}, f_{\downarrow,p}^{(s)}\} \frac{d^3 p}{(2\pi\hbar)^3}, \tag{16}$$

where n_{ph} is the photon density, shows that the photocurrent may be rewritten in the form

$$I_{ph} = -e \sum_{s=1,2} \int_{\Omega_s} dr \left(\langle \alpha_{\uparrow,p}^{(s)} \rangle - \langle \alpha_{\downarrow,p}^{(s)} \rangle \right) \frac{dn_{ph}^{(s)}}{dt}, \tag{17}$$

which makes it clear that its magnitude depends on the net rate of photon absorption/emission in combination with the spin dependence of the effective transparency of the point contact. From equation (14), one notes that the microwave-induced current changes sign at $V = V^*$, i.e. when the rate of photon emission by 'hot' electrons begins to exceed the rate of photon absorption.

The close association between the electron transport and photon radiation processes allows us to express the photocurrent in terms of the power of emission and absorption of photons by electrons in the point contact. Using equations (2), (4) and (7), one finds that the net emitted power due to resonant ($\hbar\omega = 2\mu_B H$) absorption and emission of photons in the irradiated point contact, defined as $P(V) = \hbar\omega \int dr \, dn_{ph}/dt$, can be expressed as

$$P(V) = P_0 \left(-1 + \frac{3}{2} \frac{V}{V^*} \right). \tag{18}$$

Here,

$$P_0 = \frac{\pi}{2} \frac{c}{v_F} \left(n_0 \Omega_{PC}^{(2)} \right) \frac{|\mu_B h_{ac}|^2}{\varepsilon_F} \omega \tag{19}$$

is the absorbed power due to photon absorption, while the second term in equation (18) is the emitted power due to photon emission from the point contact.

Comparing equations (14) and (19), one finds that

$$j_{ph}(V) = \frac{3}{4} \frac{V - V^*}{V^{*2}} P_0, \tag{20}$$

which makes it possible to find the power P_0 absorbed from the electromagnetic field by measuring $\mathrm{d}j_{\mathrm{ph}}(V)/\mathrm{d}V$ (see equation (14)) after first having determined V^* from the condition $j_{\mathrm{ph}}(V^*) = 0$. Furthermore, the net emitted power $P(V)$ can be determined by measuring $j_{\mathrm{ph}}(V)$ with the help of equations (20) and (18).

So far, we have shown theoretically that an inverted spin population is accumulated in a voltage-biased point contact between a ferromagnet (F) and a normal metal (N). For a contact of linear dimension $d \sim 10\,\mathrm{nm}$, biased by a voltage V, and with a spin polarization of 30% at the F/N interface ($\beta_{\mathrm{tr}} \sim 0.3$), we find that the corresponding magnetic moment injected into the contact region is $\delta M \sim 10^6\,\mu_{\mathrm{B}}\,eV/\varepsilon_{\mathrm{F}}$. We have, furthermore, shown that if the point contact is irradiated by an electromagnetic field, photon-induced electron spin-flip scattering gives rise to a peak in the relative change of the point contact resistance, $\Delta R/R$, as a function of the irradiation frequency. The peak appears when the frequency is resonant with the Zeeman splitting in the normal-metal spectrum of conduction electrons, which for an external magnetic field of $1\,\mathrm{T}$ occurs at $30\,\mathrm{GHz}$. The net power, $P(V)$, generated by the stimulated emission of photons in the electron spin-flip relaxation process can be determined by measuring the photon current $j_{\mathrm{ph}}(V)$ defined in equation (14). In the experiment discussed below, a point contact is continuously irradiated by 10–$100\,\mathrm{GHz}$ microwaves. For a typical radiation power of $10\,\mathrm{mW}$, the resulting amplitude (h_{ac}) of the magnetic component of the electromagnetic field inside the point contact is approximately $30\,\mathrm{mT}$. For such a field, we find that $\Delta R/R \sim 0.01$–0.10% and that $P(V)$ is given by equation (18) with $P(0) \sim 1$–$10\,\mathrm{pW}$, with $P(0)$ being the power absorbed from the electromagnetic field due to photon absorption in the contact region. These estimates show that an experimental implementation of the proposed spin-laser effect in magnetic point contacts is feasible and is demonstrated below. Two comments are in order. The neglect of spin-flip scattering in the normal metal due to magnetic impurities or spin–orbit interaction is well justified since the point contact size of $10\,\mathrm{nm}$ is one to two orders of magnitude smaller than the spin-diffusion length in a typical normal metal such as Cu. Another possible imperfection is spin perturbations that can occur in nano-constrictions, especially in external fields applied opposite to the magnetization in the ferromagnetic electrode (needed for spin-population inversion). One would need a very hard ferromagnet unaffected even at the interface by a reversing field of $1\,\mathrm{T}$, such as transition metal–rare earth alloy. There is another, rather interesting solution employing a spin-minority injector, where possible spin perturbations are actually fully suppressed by the high Zeeman field. This latter configuration is illustrated experimentally below.

5. Stimulated photon emission in FeCr/Cu point contacts

In this section we provide experimental evidence for the effect described above. The system is a point contact of tip-surface type, between a ferromagnetic film and a nonmagnetic tip made of Cu. The ferromagnetic material chosen for this experiment is a known minority-carrier Fe70Cr30 alloy [13], in which the majority of the conduction electrons have their magnetic moments opposite to the local magnetization and therefore spins parallel to the local magnetization (conduction electrons with magnetic moments parallel to the local magnetization are a minority). This inverse spin polarization is approximately 30% for the chosen alloy composition. The use of a minority-spin injector offers a rather special configuration for creating a strong Zeeman splitting, which is desirable for detecting the laser effect discussed above. An external magnetic field applied parallel to the magnetization of the minority injector automatically is anti-parallel to the net injected magnetic moment in Cu. This produces the
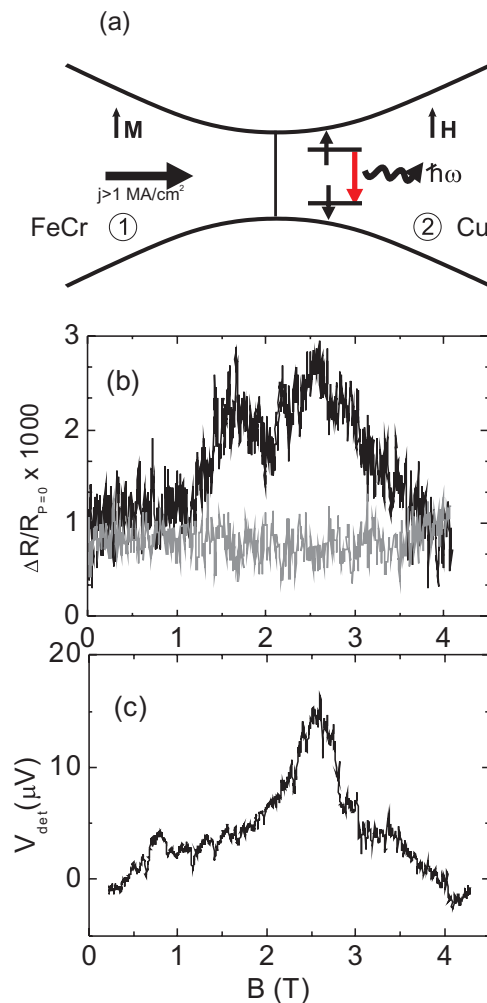
Figure 3. (a) Schematic illustration of spin-flip photon emission in an F/N point contact with a ferromagnetic electrode of the spin-minority type. The injected electrons are spin-split by an external field **H** applied parallel to the magnetization **M** of the injector, and the spin-up and spin-down levels are inversely populated. (b) Measured resistance change, $\Delta R/R_0$, due to irradiation ($f = 64$ GHz, $P_{exp} = 10$ mW) of a point contact between a Cu tip and a Cu[100 nm]/Fe$_{0.7}$Cr$_{0.3}$(50 nm)/Cu(3 nm)–Cu. The black (grey curve) is the result with the radiation switched on (off), $T = 4.2$ K and $R_0 = R(P_{exp} = 0,$ $V \rightarrow 0) = 10.6\,\Omega$ (corresponding to a point contact diameter $d_{PC} \sim 10$ nm). (c) Detector voltage locked-in to the chopping frequency (2 kHz) of the irradiating microwave field (64 GHz). This voltage is directly proportional to the irradiation-induced change in the point contact resistance (the point contact is not the same as in (a)); $T = 4.2$ K, $V_{bias} = -0.16$ mV, $R_0 = 20\,\Omega$ corresponding to $d_{PC} \sim 5$ nm.

desired spin-population inversion, with the high-energy level more populated by the injected polarized electrons than the low-energy level. Since the field is parallel to the injector's magnetization, its magnitude can be increased arbitrarily high and the spin-population inversion condition would only improve. A field of a few tesla yields a Zeeman splitting of the order

of 100 GHz, well outside the 1–10 GHz range typical for spin-torque dynamics. (We note also that the bias current of the order of 10 μA used below is two orders of magnitude lower than that typically required for inducing spin-torque effects—see, e.g., our recent results [14] for details.) This allows us to effectively separate the spin-photonic effects discussed herein from the spin-torque effects in the system. Furthermore, a high field in excess of 2 T leads to an essentially perfect magnetic alignment in the ferromagnet, including the interfacial spins in the nano-constriction, which greatly simplifies the interpretation of the experiment. This minority-injector configuration of stimulated spin-flip photo-emission is illustrated in figure 3(a).

The experimental arrangement in terms of producing point contacts and microwave irradiating them was discussed in detail in our recent publications [14, 15]. Here we concentrate on the region in the phase space of the system, in terms of the bias current and irradiation frequency, where the previously reported effects of spin-torque dynamics are absent. The irradiation frequency is 64 GHz, corresponding to a Zeeman field of approximately 2.3 T for a free electron (appropriate for Cu). The resistance with the microwave power off is essentially flat within the noise floor of the measurement, in the entire field range of 4 T. This background is subtracted from the resistance measured with the microwave power on. The difference is then normalized and shown in figure 3(b) as a function of field. The resistance becomes bell-shaped under irradiation, centered around 2.5 T, corresponding well to the expected Zeeman splitting at 64 GHz. The magnitude of the measured $\Delta R/R$ is of the order of 0.1%, which also agrees well with the above theoretical predictions for this point contact geometry. To improve the signal-to-noise ratio, the microwave power was chopped at 2 kHz and the resistance was measured using a lock-in amplifier referenced to the chopping frequency. The lock-in signal is then directly proportional to the difference in resistance with and without the irradiation. The resulting detector voltage measured for a FeCr/Cu point contact (different from that in (b)) is shown in figure 3(c). A pronounced peak in the vicinity of the expected Zeeman splitting is evidence for a relaxation process stimulated by the microwave field. This process has a resonant character in terms of its field–frequency condition, coinciding with that for stimulated photon emission by spin-flip relaxation.

In conclusion, we have shown that a suitably implemented spin injection mechanism can be used to achieve tunable photon emission by a metal. This effect has great potential for new types of spin-based lasers, which are expected to have extremely high optical gain compared to, e.g., semiconductor lasers [7].

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