New method of the spin-polarization detection in tunnel junctions ferromagnet – insulator – charge density wave metal

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Tunnel junction between a metal partially gapped by charge density waves metal (CDWM) and a ferromagnet (FM) in an external magnetic field is considered. Only the Zeeman paramagnetic effect is taken into account. It is shown that the peaks in the dependence of differential conductance vs. voltage, induced by the CDW gap, split, each peak having a predominant spin polarization. This effect makes it possible to electrically measure the polarization of current carriers in FMs.

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Spin electronics (spintronics) has recently become an extremely important area of science as well as the flourishing branch of industry [1 – 3]. Ferromagnets (FMs) with a metallic character of electrical conductance are an integral part of various magnetoelectronic devices including, in particular, magnetic tunnel junctions. Spin polarization at the Fermi level is the basic parameter, which describes the FM properties relevant for those applications. It is most frequently defined as

$$P = \frac{N_{FM-} - N_{FM+}}{N_{FM-} + N_{FM+}}, \qquad (1)$$

where $N_{FM\mp}$ is the density of states (DOS) of the "majority" ("minority") electrons with spins directed opposite to (along) the quantization axis, respectively, at the Fermi level. This definition is directly applicable for the interpretation of photoemission or inverse photoemission measurements [4, 5], whereas the account of different interface attributes requires essential modifications of Eq. (1) during electron transport studies [3, 6, 7]. Anyway, even in strong ferromagnets, P falls short of the saturation value of 100%, which was attained not long ago for the so-called half-metals, e.g., CrO_2 and manganites [6, 8]. Hence, an experimental estimation of P is highly needed both for practical applications and to check electronic band-structure calculations and theories of magnetic tunneling.

The main existing transport methods for the determination of P comprise measurements of (i) tunnel currents between two FMs [2, 3], (ii) tunnel currents between FMs and superconductors (S) in the external magnetic field H [9], (iii) point-contact conductance in junctions involving two ferromagnetic electrodes [10], and (iv) point-contact conductance with Andreev reflections at a FM/S interface [11]. In this article we show a new possibility to deduce P from transport studies.

Our approach is an outgrowth of the method suggested by Tedrow and Meservey (see review [9]) for a S–I–FM junction (I stands for an insulator), according to which P may be expressed in terms of the differential tunnel conductivity $G(V) \equiv dJ/dV$ of a quasiparticle tunnel current J taken at definite voltages V in a non-zero external magnetic field H. The main shortcoming of using the S–I–FM tunneling is the dominating role of the orbital (Meissner) depairing over the paramagnetic suppression of superconductivity in most circumstances [12]. Hence, the thin-film geometry of S-electrodes is unavoidable and the choice of suitable superconducting covers is troublesome.

Therefore, we analyse a new class of partners for the FMs, namely, metals partially gapped by charge density waves (CDWs) – CDWMs [13]. So, the tunneling scheme has now the form CDWM-I-FM. An external magnetic field stimulates a paramagnetic effect in the CDWM analogous to that in superconductors [14, 15]. On the other hand, the giant diamagnetic (Meissner) response does not appear for CDWMs at all because this state lacks for superfluid properties [16]. As for the spin-orbit coupling, which leads to harmful spin-flips, its role can be diminished by an adequate choice of the light-atom constituents for CDW materials.

While examining current-voltage characteristics (CVCs), for the sake of definiteness, the bias V is chosen as a voltage difference between the FM and the

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CDWM: $V \equiv V_{\rm FM} - V_{\rm CDWM}$. It is presumed that for high enough H all domains inside the ferromagnet are completely aligned in the field direction. The properties of the partially-gapped CDWM are characterized in the framework of the Bilbro–McMillan model [13, 17]. According to this approach, which describes with an equal success both the Peierls insulating state in quasi-one-dimensional substances and the excitonic insulating state in semimetals, the Fermi surface (FS) consists of three sections. Two of them ($i = 1, 2$) are nested, with the corresponding fermion quasiparticle spectrum branches obeying the equation

$$\xi_1(\mathbf{p}) = -\xi_2(\mathbf{p}+\mathbf{Q}), \qquad (2)$$

where $\mathbf{Q}$ is the CDW vector. So, the electron spectra here become degenerate (d) and a CDW-related order parameter appears. The rest of the FS ($i = 3$) remains undistorted under the electron-phonon (the Peierls insulator) or Coulomb (excitonic insulator) interaction and is described by the non-degenerate (n) spectrum branch $\xi_3(p)$. A uniform dielectric (CDW) order parameter $\tilde{\Sigma}$ appears only on the nested FS sections. The CDWM phase is described, in the presence of the external magnetic field H and without making allowance for any orbital diamagnetism, by a system of the Dyson equations for the normal temperature Green's functions.

For present purposes one can disregard the diamagnetic effect while investigating the spin-split peaks of the $G(V)$ for CDWMs. Of course, it does not mean that T_d itself does not depend on H if one goes beyond the approximation adopted in this publication. Nevertheless, the experiment showed that the field-induced CDW suppression $\Delta T_d \propto -H^2$ and is quite small indeed. For example, in the A15 compound V_3Si with $T_d(H=0) = 20.15$ K even for a very large $H = 156$ kOe the correction is 0.6 K [18].

Thus, while studying the spin splitting in CDWMs, no restrictions from above appear on the H amplitude other than the natural paramagnetic limit $\mu_B^* H < \Sigma_0\sqrt{\mu/2}$, where $\mu_B^* = e\hbar/2m^*c$ is the effective Bohr magneton, e is the elementary charge, $\hbar$ is Planck's constant, c is the velocity of light, and m^* is the effective mass of the current carriers, the quantity $\Sigma_0 \equiv \frac{\pi}{\gamma} k_B T_d$ is the amplitude of the CDW order parameter at the temperature $T = 0$, k_B and $\gamma = 1.78\ldots$ are the Boltzmann and Euler constants, respectively, and μ, with $0 \le \mu \le 1$, is a relative portion of the FS sections gapped by CDWs. Since we are going to deal with smaller fields, the intriguing problem of the nonhomogeneous state [14] analogous to the Larkin–Ovchinnikov–Fulde–Ferrel one in ordinary superconductors for $H \ge H_p$ will be not touched upon. Hence, we assume the function $\tilde{\Sigma}(T)$ to be the BCS-like one.

We calculated $J(V)$ according to the expressions which can be straightforwardly obtained by the Green's function method of Larkin and Ovchinnikov [19]. Generally, the current $J(V)$ consists of six components:

$$J(V) = \sum_{\substack{f=n,d,c\\ s=-,+}} J_{fs}(V), \qquad (3)$$

$$J_{n\mp} = \frac{(1-\mu)(1\pm P)V}{2eR}, \qquad (4)$$

$$J_{d\mp} = \frac{\mu(1\pm P)}{4eR} \times \times \int_{-\infty}^{\infty} d\omega\; K(\omega,V,T)\,|\omega \pm \mu_B^* H|\, f_\pm(\omega,H,\Sigma); \qquad (5)$$

$$J_{c\mp} = \frac{\mu(1\pm P)\tilde{\Sigma}}{4eR} \times \times \int_{-\infty}^{\infty} d\omega\; K(\omega,V,T)\mathrm{sign}\,(\omega \pm \mu_B^* H)\, f_\pm(\omega,H,\Sigma). \qquad (6)$$

Here

$$K(\omega,V,T) = \tanh\frac{\omega}{2T} - \tanh\frac{\omega - eV}{2T}, \qquad (7)$$

$$f_\pm(\omega,H,\Sigma) = \frac{\theta\left(|\omega \pm \mu_B^* H| - \Sigma\right)}{\sqrt{\left(\omega \pm \mu_B^* H\right)^2 - \Sigma^2}}, \qquad (8)$$

the upper (lower) sign corresponds to the "majority" ("minority") spin orientation, respectively, R is the "normal state" (above T_d) resistance of the junction, $\theta(x)$ denotes the Heaviside theta function. The current components depend on the phase φ of $\tilde{\Sigma} = \Sigma e^{i\varphi}$, whereas the thermodynamic properties of CDW superconductors are degenerate with respect to s. We suggested that quasiparticles from all the FS sections make their contributions to the total current proportional to the DOS of the relevant section. That means an absence of any kind of the directional tunneling, which is possible, in principle [20].

An important difference between the problem in point and its counterpart appropriate to the BCS superconductivity is the emergence of the terms $J_{c\mp}$. They reflect the existence of the electron-hole pairing in CDWMs, originated from the interband Green's function G_c, and have other behavior than the remaining terms linked to the conventional normal Green's functions. To a large extent, $\mathcal{G}_c$ is analogous to the anomalous Gor'kov Green's function $\mathcal{F}$, which, however, determines the Josephson rather than quasiparticle tunnel current. The appearance of terms (6) leads to the drastic *asymmetry* of the CVC of non-symmetrical tunnel junctions involving CDWMs. In incommensurate CDWMs, the order parameter phase φ is arbitrary. However, to understand the picture qualitatively it is enough to restrict the consideration to the particular case of commensurate CDWs, when φ is either 0 or π. Then, relevant equations describe tunneling between, e.g., excitonic insulators.

Conductivities $G_{fs}(V)$ can be obtained by differentiating relevant Eqs.(4)–(6). At $T = 0$, the corresponding analytical expressions become

$$G_{n\mp}(V) = \frac{(1-\mu)\,(1 \pm P)}{2R}, \qquad (9)$$

$$G_{d\mp}(V) = \frac{\mu\,(1 \pm P)}{2R}\text{sign}(V)\,(eV \pm \mu_B H)\,f_{\pm}(eV, H, \Sigma), \qquad (10)$$

$$G_{c\mp}(V) = \frac{\mu\,(1 \pm P)\,\tilde{\Sigma}}{2R}\text{sign}(V) f_{\pm}(eV, H, \Sigma). \qquad (11)$$

Naturally, the sum of the G_n-terms gives the constant $(1 - \mu)/R$.

The dependences of the dimensionless conductance RdJ/dV for the CDWM-I-FM junction on the dimensionless bias voltage eV/Σ_0 are shown in Fig.1 for $\tilde{\Sigma} > 0$. Other dimensionless parameters of the problem are the normalized external magnetic field $h = \mu_B^* H/\Sigma_0$ and temperature $t = k_B T/\Sigma_0$. It is readily seen that $G(V)$ is highly asymmetrical, contrary to the symmetrical patterns appropriate to tunnel junctions involving superconductors no matter those junctions are symmetrical or not [21]. Mathematically it stems from an almost total compensation between $G_d(V)$ and $G_c(V)$ logarithmic singularities at voltages of one sign and their enhancement at voltages of the other sign (for the adopted choice $\tilde{\Sigma} > 0$, it means negative and positive V, respectively). In the absence of the external magnetic field and spin polarization, such an asymmetrical behavior of $G(V)$ was obtained by us earlier [22–24]. When H is switched on, the electronic DOS peak splits as in the case of superconductors [9, 25]. The spin-splitting is noticeable, however, only for one CVC branch ($V > 0$ in the case $\tilde{\Sigma} > 0$, the other branch contains only remnants of the gap-related features). Thus, a simple algebraic procedure of Tedrow and Meservey of finding P from a kit of

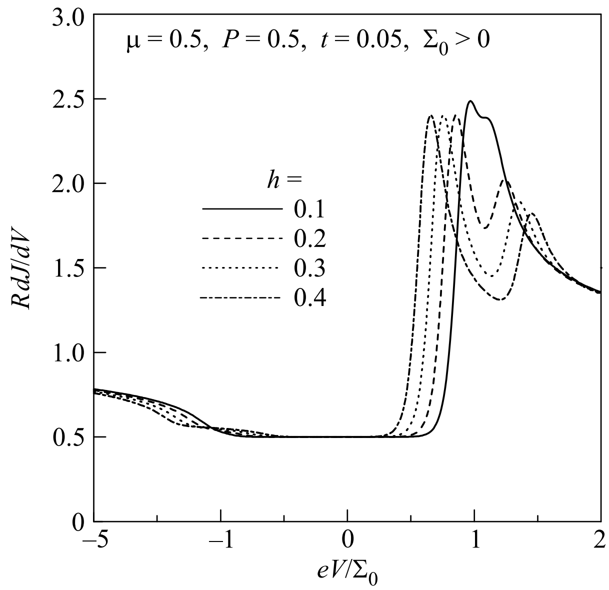

Fig.1. Dependences of differential conductance on bias voltage V across the tunnel junction made up of charge-density wave metal (CDWM) and ferromagnet (FM) for various external magnetic fields H. See explanations in the text

G values measured at certain V's and H, successful for S-I-FM junctions [9, 26], seems to fail for CDWM-I-FM ones, because this method needs the values of conductance on both voltage branches.

Nevertheless, the advantage of the set-up, proposed here to detect spin-polarization-induced changes, consists in a more clear manifestation of the spin-splitting effect for one CVC branch and in a larger scale of Σ for existing CDWMs as compared to the energy gaps Δ in their superconducting counterparts, with the dependences $G(V)$ being very sensitive to the value of P. Moreover, the CVCs crucially depend on the sign of $\tilde{\Sigma}$ in the CDWM. Let us first consider the case $\tilde{\Sigma} > 0$ [Fig.2, panel (a)]. One can see how the spin-splitting pattern is distorted for a ferromagnetic counter-electrode ($P \neq 0$) in comparison with the nonpolarized case ($P = 0$). In particular, the minority-spin peak, which is positioned farther from the zero bias than the majority one, is reduced with increasing P, so that for the complete polarization ($P = 1$, this limit is attainable in half-metallic ferromagnets [6, 8, 10]) it disappears and only one (majority) peak survives.

When $\tilde{\Sigma} < 0$ [Fig.2, panel (b)], the minority-spin peak disappears with increasing P similarly to the opposite case $\tilde{\Sigma} > 0$, but now it is situated closer to the

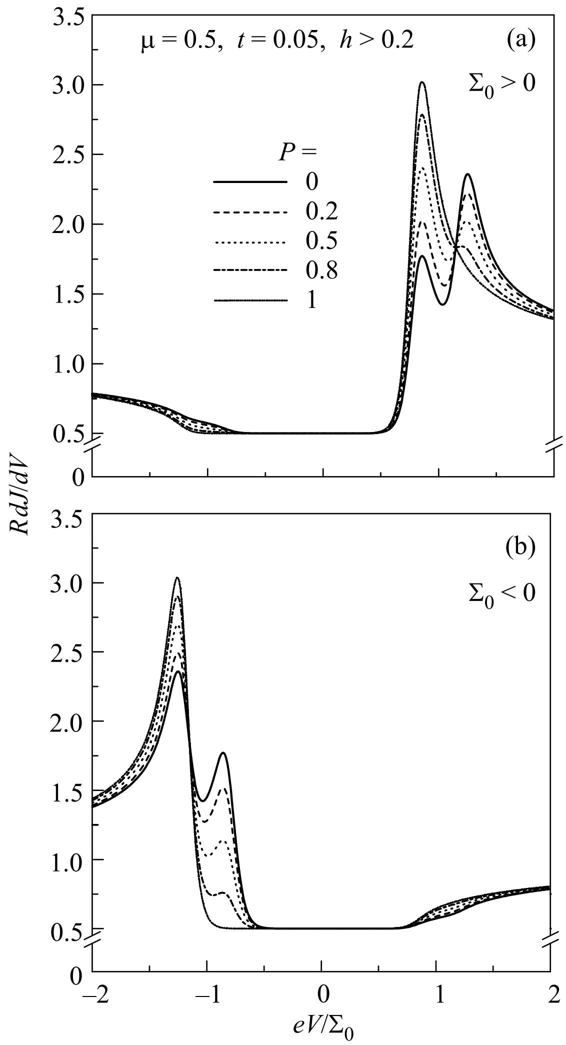

Fig.2. The same as in Fig.1 but for various polarizations P of electrons on the FM Fermi level. Panels correspond to different sign of the dielectric order parameter $\tilde{\Sigma}$ in CDWM. See explanations in the text. (a) $\Sigma_0 > 0$, (b) $\Sigma_0 < 0$

zero bias than the majority one. Hence, the "modified" symmetry relationship

$$G(-\tilde{\Sigma}, V) = G(\tilde{\Sigma}, -V), \tag{12}$$

appropriate for junctions involving normal or superconducting CDW electrodes and non-ferromagnetic normal metal counter-electrodes (cf. $P = 0$ curves on both panels), is no more valid, and the CVCs for $H \neq 0$ lack any symmetry properties. Then different signs of $\tilde{\Sigma}$ can be distinguished by CVC measurements. It is worth to underline once more that the actual $\tilde{\Sigma}$ sign for a specific junction might occur at random, induced by unpredictable fluctuations, since the bulk thermodynamic free energy of normal or superconducting CDW metals does not depend on this sign [27–29].

At the same time, the predicted effect is highly sensitive to the temperature. The smoothing effect of the latter is shown in Fig.3. The Zeeman splitting becomes

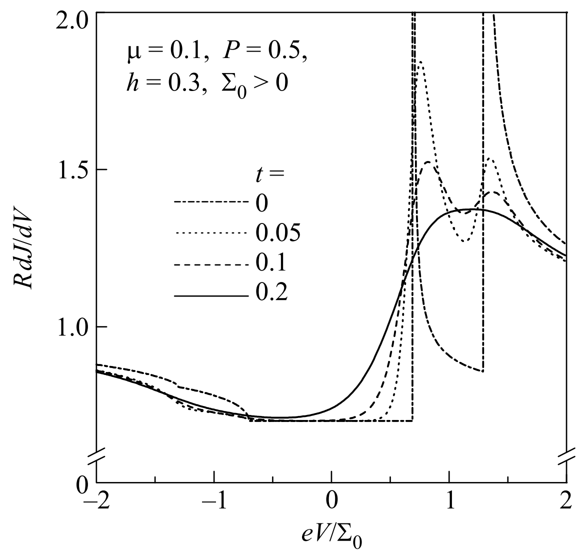

Fig.3. The same as in Fig.1 but for various temperatures T

unobservable already at a relatively small value $t = 0.2$. However, CDW metals with T_d's of the order of 10 – 15 K are now available [30, 31] with the corresponding destructive magnetic fields $H \approx 180 - 270$ kOe, which are attainable experimentally. Hence, larger magnetic fields may be applied to detect the paramagnetic spin-splitting against the background of various smearing factors, temperature included.

To illustrate that the predicted phenomenon can be observed indeed, let us consider the spin-orbit smearing in $2H$-$NbSe_2$ with the superconducting critical temperature $T_c = 7.2$ K and $T_d = 33.5$ K [13] and compare it with that in Al where the spin-splitting effect was observed [9]. We shall confine the consideration for $2H$-$NbSe_2$ to the CDW-induced peaks only. The spin-orbit scattering in superconductors is governed by a single parameter $b = \hbar/(3\tau_{so}\Delta) \propto Z^4/\Delta$, where $\hbar/\tau_{so}$ is the spin-orbit scattering rate, Z is the material atomic number, and Δ is the superconducting gap. For Al, $Z_{Al} = 13$ $\Delta_{Al} \approx 0.4$ meV, and $b_{Al} \approx 0.05$, while even the value of 0.2 ensures the satisfactory spin-splitting of the Δ-driven peaks [9, 25]. On the other hand, using the same ideas, $b_{2H-NbSe_2} \propto Z^4_{Nb}/\Sigma$ for $2H$-$NbSe_2$, where $\Sigma \approx 34$ meV is the measured dielectric gap [32] and $Z_{Nb} = 41$ ($Z_{Se} = 34$, which may only improve our estimation). Assuming the elastic scattering rates to be of the same order of magnitude in both the materials, we obtain $b_{2H-NbSe_2} \approx 1.2 b_{Al} \approx 0.06$. Thus, even if the spin-splitting of the Δ-induced peaks in $2H$-$NbSe_2$ is smeared, that of the CDW-triggered ones should remain resolved. It is the more so because the superconductivity- and CDW-induced CVC peaks are well separated from one another (cf. the values of T_c and T_d for $2H$-$NbSe_2$ quoted above).

We would like to indicate several other possible candidates for the CDW partner of FMs in tunnel sandwiches. These are organic CDW metals α-$(ET)_2MHg(SCN)_4$ (M = K, Tl, Rb) [15, 30] and $Per_2[M(mnt)_2]$ (Au, Pt) [31]. The main weak point of those materials is the presence of heavy elements Hg, Tl, Au or Pt, which is dangerous because of a possible spin-orbit smearing of the spin-split $G(V)$ peaks. A two-leg ladder compound $Sr_{14-x}Ca_xCu_{24}O_{41}$ also seems very promising. Really, Ca doping alters T_d and Σ over a remarkably wide range from 210 K and 130 meV, respectively, for $x = 0$ down to 10 K and 3 meV for $x = 9$ [33].

On the whole, the application of the fruitful ideas, earlier developed for superconductors [9], to normal partially CDW-gapped metals seems useful for studying those strongly correlated objects.

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