SUPERCONDUCTIVITY

Controlling magnetism

Manipulation of the magnetic state in spin valve structures by superconductivity has now been achieved, opening a new route for the development of ultra-fast cryogenic memories.

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Spintronics is a rapidly developing field that allows insight into fundamental spin-dependent physical properties and the development of practical applications — such as the read head sensors for hard drives in computers. Recently, so-called superconducting spintronics, which involves structures formed by ferromagnetic (FM) and superconducting (SC) layers, has emerged, promising advances in the fundamental understanding of the competition between superconducting and magnetic ordering, as well as new device functionalities[1]. Whereas previous works have demonstrated tunability of the superconductive properties by controlling the magnetization of the FM layers, Yi Zhu and colleagues[2] now report a mechanism that allows the control of magnetic properties through the superconductivity.

The most conventional spintronic element consists of two ferromagnetic layers coupled by a spacing layer. Its electrical resistance depends on the relative alignment of the magnetization directions of the two ferromagnets, which can be modified either by applying external magnetic fields or by injecting spin-polarized electrons[3]. With thin enough SC spacing layers, the superconductivity can be controlled by the magnetic order of the FM layers, as the superconducting proximity effect leads to leakage of superconducting correlations into the neighbouring FM layers. For instance, tuning of the superconducting transition temperature[4,5] and the superconducting critical current of Josephson devices[6] has been demonstrated. In these previous studies the proximity effect was achieved in the regime in which the energy required to switch the magnetization is significantly larger than the superconducting condensation energy, and therefore the influence of the superconductivity on the magnetic properties was negligible[7–9].

In order to illustrate the conditions for realization of superconducting exchange coupling, let us consider a FMI/SC/FMI structure — here, FMI stands for ferromagnetic insulator — where the magnetization vector of the top FM layer, $\mathbf{M}_1$, is parallel to the magnetization vector of the thicker bottom FM layer, $\mathbf{M}_2$. In this structure it is possible to realize superconductivity in a thin SC layer even if its thickness d_S is comparable to the superconducting coherence length ξ_S. According to De Gennes[10], the ground state of the system depends on a balance between the coupling energy between $\mathbf{M}_1$ and $\mathbf{M}_2$ and the superconducting condensation energy in the SC film. As shown in Fig. 1, the condensation energy depends on the magnetic configuration, being smaller with parallel (left panel) than with antiparallel (right panel) orientation of the magnetizations. In the first case, electronic scattering at the interfaces will lead to a realization of the majority of the states with the spin direction along the magnetization directions $\mathbf{M}_1$ and $\mathbf{M}_2$. The number of spin-singlet Cooper pairs will therefore be reduced compared to the equilibrium value at a given temperature. In the second case, the interface scattering of electrons does not lead to any imbalance between the spin orientations due to the antiferromagnetic ordering of the FM layers. Therefore, the superconducting order parameter that characterizes the Cooper pair density and determines the free energy of the superconductor is higher for an antiparallel alignment of $\mathbf{M}_1$ and $\mathbf{M}_2$ (Fig. 1). As a result, the antiparallel magnetic configuration has lower energy and provides a new mechanism of effective exchange coupling between the two FM layers[10]. This mechanism is effective when at least one of the FM films is sufficiently thin and the magnitude of the coupling does not exceed the magnetization switching energy. The SC layer should be thin as well, because for $d_S \gg \xi_S$ the spin imbalance effect will not be operative anymore and exchange coupling will decay exponentially with increasing d_S.

Zhu and co-workers use a series of GdN/Nb/GdN trilayer configurations with various thicknesses of the superconducting Nb interlayer, and study the resistance as a function of applied magnetic field and

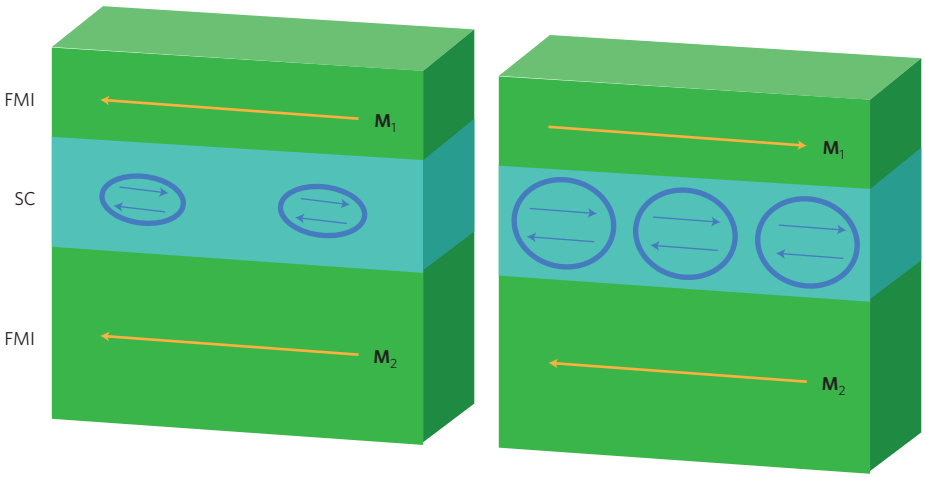

Figure 1 | Superconducting exchange coupling in a FMI/SC/FMI trilayer. The Cooper pairs in the SC layer are depicted as blue circles with pairs of blue arrows inside. The order parameter of the superconductor is higher and the corresponding free energy of the trilayer is lower for an antiparallel alignment of the magnetizations of the top and bottom layers ($\mathbf{M}_1$ and $\mathbf{M}_2$, respectively), which are represented by the larger size of the Cooper pairs in the right panel. The number of Cooper pairs — which provide an effective coupling between the ferromagnets — depends on the relative alignment of the magnetizations, being also larger when $\mathbf{M}_1$ and $\mathbf{M}_2$ are antiparallel.

magnetization hysteresis loops of these devices. These measurements allow them to demonstrate the new type of exchange coupling due to the superconductivity in the interlayer. To prove the key role of the superconductivity on their experiments, they made a number of tests, including the substitution of Nb by a non-superconducting Ta interlayer and the addition of thin dielectric AlN layers between GdN and Nb. In both cases the effects vanished, confirming that the observed effects are indeed due to superconductivity in the interlayer and do not stem from stray fields.

The effect observed by Zhu and collaborators may allow the development of ultra-fast superconducting memories. Other work[11] shows there are viable structures that also provide possible routes to realize low-temperature memory elements. A number of proposals to build fast high-density superconducting memory put forward recently[12–15] are based on spin valve structures with two or more FM layers and are compatible with the structures developed by Zhu and colleagues. An interesting possibility for future research would be to modulate the superconductivity in thin superconducting layers due to quasiparticle non-equilibrium effects in FMI/SC/FMI structures. It could be achieved either by injecting charge carriers from external superconducting reservoirs[16] or by spin injection from additional ferromagnetic layers[17] coupled to the FMI/SC/FMI structure. Modulation of superconducting properties of the SC layer may in turn control the magnetic state of the junction. The findings of Zhu and collaborators will certainly stimulate further research in the field of superconducting spintronics and development of novel devices for memory applications. ❐

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ORGANIC ELECTRONICS

One model to rule them all

A single transport function has been developed to describe the temperature and energy dependence of charge transport in insulating, semiconducting and metallic polymers.

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Conducting polymers have remained an enduringly rich area of scientific interest since the first reports of doping in conjugated macromolecules in the 1970s, which showed that these traditionally insulating plastics could, surprisingly, act as electronic materials[1]. This was the genesis of a new field, and organic polymers now exhibit a wide range of conduction phenomena — they can exist as insulators, semiconductors, or even achieve conduction rivalling that of metals[1–4]. Thus, the question of how charges travel through polymers poses not only a fundamental challenge, but also a dilemma for researchers aiming to rationally optimize their transport properties for new classes of light emitting diodes, solar photovoltaics and, recently, thermoelectrics. Writing in *Nature Materials*, Stephen Dongmin Kang and Jeffrey Snyder now propose a general description for transport in polymers based on a single transport function, which accurately describes both the temperature and energy dependence of many polymers over eight orders of magnitude in conduction[5]. This has immediate payoff, particularly for researchers in the burgeoning field of organic thermoelectrics where the relationship between the conductivity of a polymer and the amount of heat transported per carrier (Seebeck coefficient, S) has been impenetrable to theoretical description until now.

Historically, a general theory of electronic transport in polymers has been lacking in part due to the basic differences in the structure and electronic properties of polymers as compared to crystalline inorganic materials (Fig. 1). The high symmetry and translational periodicity of inorganic crystals allowed the development of simple transport models like the Boltzmann transport equation[6], which reliably explains how to change the temperature, number of electrons or holes (carrier concentration), or the mobility of carriers in semiconductors to manifest whatever transport properties are desired. By contrast, most conductive polymers are semicrystalline, comprised of crystalline domains connected by amorphous chains, and possess microscale heterogeneity[7]. As a result of this structural complexity, comprehensive discussion of transport in polymers has required a patchwork quilt of different models, each of which effectively characterizes transport only in certain regimes, breaks down in certain ways, and lacks general applicability. For example, the Heikes model describes the thermopower of localized carriers reluctantly shuffling to nearest neighbour sites (and is thus best suited for insulators or amorphous materials)[8], whereas the variable range hopping (VRH) model is more effective for doped semiconducting polymers where carriers have sufficient energy to jump to a manifold of nearby sites that are also close in energy[9]; yet neither describes metallic conduction effectively, which is the domain of the classical Mott mobility edge model developed for abrupt insulator to metal transitions[1,3,9]. Furthermore, none of these models accurately represent both the energy and temperature dependence of the carriers, which is crucial information for optimizing polymers for devices that interconvert gradients of