Viewpoint:

No loop required – transforming a tunnel junction to mimic a SQUID

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Recently there has been a trend to develop nanoscale superconducting quantum interference devices (nanoSQUIDs) with the aim to reach magnetic flux sensitivities sufficient to detect the flip of a single electron spin in close proximity (see refs [1], [2] and [3] for detailed overviews of recent developments in this area). Potential applications range from investigating magnetic ions or magnetic molecules or small spin populations in magnetic nanoparticles, to readouts for flux qubits and nanomechanical resonators. Various techniques have been reported to create the weak links (Josephson elements) in nanoSQUIDs. Some groups have developed nanoSQUIDs based on nanoscale tunnel junctions (e.g. ref [4]), but the most common approach has involved using either focussed-ion-beam (FIB) [5-7] or electron-beam patterning [8-12] of superconducting thin films to form nanoscale constrictions which act as weak links when their dimensions are comparable to the Ginzburg-Landau coherence length ξ_{GL}.

Perhaps the most commonly fabricated and easiest to operate type of nanoSQUID is the dc SQUID which consists of two parallel weak links in a small superconducting loop to which direct current and voltage connections are made. The critical current of a dc SQUID undergoes periodic modulation with increasing magnetic flux Φ applied to the loop. When current-biased in the voltage state just above the SQUID critical current, the voltage *V* measured across the SQUID undergoes periodic, quasi-sinusoidal oscillations with increasing flux. The period of the oscillation is the flux quantum Φ_0. Thus the current-biased dc SQUID is straightforward to operate as a ***flux-to-voltage*** transducer to measure small flux changes ($\delta\Phi << \Phi_0$) by applying a static flux-bias to sit on the steepest part of the *V*-Φ curve. For typical dc SQUIDs operating at liquid helium temperatures, the equivalent flux noise floor $S_{\Phi}^{1/2}$ (in units of $\Phi_0/\sqrt{\text{Hz}}$) generally scales $\propto \sqrt{L}$ where *L* is the loop inductance, which in turn scales with the loop radius ***a***. Hence the drive to develop nanoSQUIDs has been led by the desire to decrease *L* by fabricating smaller loops to achieve the best possible flux sensitivity at a given temperature.

Fabricating both nanoscale weak links and nanoscale loops whilst allowing space for wiring connections and sufficient 'bulk' of the superconducting electrodes and loop to maintain their superconducting properties is challenging. However an intriguing new approach could offer a novel solution to overcome these difficulties. Nevirkovets and Mukhanov [13] have for the first time observed quasi-sinusoidal critical current oscillations within a ***single*** Josephson tunnel junction stack containing periodic normal metal (aluminium)-ferromagnet (permalloy) multilayer structures on either side of the insulating barrier. A conventional superconductor-insulator-superconductor tunnel junction would be expected to have a critical current (I_c) versus magnetic flux response that follows a $\sin(\pi\Phi/\Phi_0)/(\pi\Phi/\Phi_0)$ dependence analogous to the optical Fraunhofer diffraction pattern of a single slit. In contrast the quasi-sinusoidal critical current oscillations observed by Nevirkovets and Mukhanov instead resemble the response expected for a dc SQUID. Their single junction structure thus mimics the electrical behaviour of a dc SQUID without the need to fabricate an actual superconducting loop, and so could be potentially exploited in future for flux sensing and related applications as a simple superconducting circuit analogue of a dc SQUID. Nevirkovets and Mukhanov show that the measured quasi-sinusoidal response varies more rapidly with applied field H compared to the field required to reach the first minimum in the single slit-like Fraunhofer pattern for an equivalently sized conventional tunnel junction. This means that the response they observe is not due to some non-uniformity or pin holes in the junction barrier leading to say two weak links in parallel within the single junction stack. They estimate the Josephson penetration depth is larger than the junction width, so that the supercurrent distribution across the junction is expected to be fairly uniform. Their further analysis also rules out the possibility that the unexpectedly rapid quasi-sinusoidal response is due to the magnetisation of the ferromagnetic layers enhancing the applied field. This leads them to speculate that the observed oscillations are instead related to some so-far unexplained interference effects within the periodic ferromagnet-normal metal multilayer structure itself (or a combination of different interference effects including between the superconducting electrodes).

The interplay of superconductivity and ferromagnetism has been studied for many years, including much recent study of superconductor-ferromagnetic normal metal heterostructures and their use to fabricate so-called π-junctions which are very desirable circuit elements for quantum computing applications [14]. The work of Nevirkovets and Mukhanov shows that there are still gaps in our theoretical understanding of the interference mechanisms in periodic ferromagnetic-normal metal structures coupled to superconducting electrodes. Their work should stimulate future theoretical and experimental developments in this area, in addition to the potential for developing new applications and circuits exploiting the phenomenon itself.

References

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