Controlled superconducting vortex creation raises hope for a dissipationless memory device.

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At the interface between superconducting and magnetic materials is a plethora of new physics. This new physics can be driven by electronic proximity effects, taking advantage of the competing orderings of the superconducting pairs and ferromagnetism. Or alternatively, new physics arises due to stray fields from the magnetic material interacting with the superconductor via the Meissner effect.

Advances in thin-films and nanolithography over the past decades have allowed the use of artificial heterostructures to explore such an interface in great detail. Spintronics (spin electronics) is concerned with creating computational devices taking advantage of the spin quantum properties of an electron in addition to the electron charge. By combining spintronics with the dissipationless property of superconductivity, superspintronic memory and logic devices have potential to be both fast and highly energy efficient [1–3].

While superconducting logic is a mature field (circuits operating at 770 GHz were demonstrated in the 1990's [4]), the memory to accompany an all superconducting computer is not as well developed [5,6]. In the late 1970's it was recognized that Abrikosov vortices (whirlpools of superconducting current which trap quantized magnetic flux in type-II superconductors) could be used in memory devices, where the presence (absence) of a vortex at the site of the detection Josephson junction would lead to a low (high) critical current through the junction [7]. Although devices based on these principles were experimentally realized, when compared to modern magnetic memory, the size of the superconducting loop used to pin and manipulate the vortex was prohibitive for application [8–10].

Broadly, a modern memory device based on superconductor/ferromagnet hybrids could operate in one of three ways:

(1) The tuning of the critical temperature of the superconductor, such that the device can either be in the dissipative or dissipationless state by the relative alignment of two or more ferromagnetic layers in a spin-valve device (so called "infinite magnetoresistance" in analogy to the giant magnetoresistance (GMR) effect in spintronics) [11].
(2) In ferromagnetic Josephson junctions containing two ferromagnets, where information can be stored by the high/low critical current state or by the "0 - π" switching of the ground-state phase difference across the two superconducting electrodes when the magnetisation of one ferromagnet is reversed [12–14].
(3) The manipulation of Abrikosov vortices to give a binary memory state (with or without vortices) as proposed by Patiño and Blamire in their recent Letter to SUST [15].

Motivated by the recent advances in superconductor/ferromagnet hybrids, an attractive route towards miniaturization of memory devices based on Abrikosov vortices is to replace large superconducting loops with lithographically defined nano-magnets or ferromagnetic domain walls. Stray fields emanating from nano-magnet arrays or domain walls provide preferential pinning sites for an Abrikosov vortex, as the type-II superconductor acts to screen the stray fields. By reconfiguring the nano-magnet array or domain wall, it is possible to modify the pinning potential on the vortex, creating multiple states for a memory device [16–19]. A noteworthy system in which to realise such effects are artificial spin ices, where magnetic frustration provides a rich phase diagram of magnetic configurations [20].

In their recent letter, Patiño and Blamire use ferromagnetic domain walls for a somewhat different purpose in their superconductor/ferromagnet hybrids: to generate the Abrikosov vortices. In their experiment, they use a thick Co (40 – 55 nm) ferromagnetic layer coupled to a thin Nb (25 nm) superconducting layer (although 50 nm of Co sounds thin, it is very thick in comparison to the length scale that superconducting correlations can penetrate the Co layer, $\approx$ 1 nm).

Employing traditional bulk magnetometry techniques, the authors measure the magnetic response of the bilayer under applied magnetic field. Sweeping from a large positive field to zero, the superconductor gains a large positive magnetisation due to in-plane screening processes. At a small negative field, the ferromagnet's magnetisation is reversed and suddenly (unexpectedly) the magnetisation signal from the superconductor drops to nearly zero, where it remains up to large negative applied field values.

What happens during reversal of the ferromagnet? Patiño and Blamire propose that the key ingredient to the vanishing magnetic signal are Bloch type domain walls in the adjacent Co, which have stray fields pointing out-of-plane, directly into the superconductor. These stray fields penetrate the Nb, which in turn causes the formation of Abrikosov vortices responsible for the sudden magnetisation drop. What is remarkable, is that even when the domain walls are removed (by saturation with an applied magnetic field), the Abrikosov vortices remain and continue to modify the magnetic properties of the Nb. Thus, the Nb "remembers" the magnetisation reversal of the Co, which could be the basis of energy-efficient data storage in cryogenic superspintronics.

Bulk or scanning magnetometry techniques, although very useful to characterize the Abrikosov vortex states, are not ideal read-out mechanisms for a memory device. It is significant, therefore, that the two states of the memory proposed by Patiño and Blamire are also electronically detectable, due to the modification to the critical (depairing) current in the vortex state [21].

Fuelled by advances in hybrid structures, the study of Abrikosov vortices is currently in somewhat of a renaissance [15–20]. In addition to the possibility of devices, it would certainly be interesting for future research to address the inverse of the effect studied by Patiño and Blamire - can the Abrikosov vortex state imprint domain walls or spin textures onto an otherwise uniform ferromagnet?

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