Localized Magnetic Fields in Arbitrary Directions Using Patterned Nanomagnets

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ABSTRACT Control of the local magnetic fields desirable for spintronics and quantum information technology is not well developed. Existing methods produce either moderately small local fields or one field orientation. We present designs of patterned magnetic elements that produce remanent fields of 50 mT (potentially 200 mT) confined to chosen, submicrometer regions in directions perpendicular to an external initializing field. A wide variety of magnetic-field profiles on nanometer scales can be produced with the option of applying electric fields, for example, to move a quantum dot between regions where the magnetic-field direction or strength is different. We have confirmed our modeling by measuring the fields in one design using electron holography.

KEYWORDS Magnetic field, nanomagnet, permalloy, electron holography

Surface split-gate technology,1,2 with controllable local electric fields on nanometer length scales, has revolutionized quantum electronics, allowing the manipulation of even single electrons.3–5 Spatially patterned magnetic films have a long history, for example, in bubble memory,6 but on scales required for spintronic and quantum information technology, techniques are less well developed. Larger fields may be produced by magnetically hard materials or larger ferromagnets.7–12 These all produce a local field parallel to the external field. Strip lines, the other common approach, produce only moderately small fields.14–16 In this letter, we present designs of patterned magnetic elements that produce remanent fields confined to chosen, submicrometer regions, in directions perpendicular to an external initializing field. This technique can be tailored to produce a wide variety of magnetic-field profiles on nanometer scales with the option of applying electric fields, for example, to move a quantum dot between regions where the magnetic-field direction or strength is different as proposed and demonstrated by the experiments of Pioro-Ladrière et al.12,13 We have fabricated one such design in permalloy and confirmed the accuracy of the modeling by measuring the fields using electron holography.

In this letter, we present designs of patterned magnetic elements that produce remanent fields confined to chosen, submicrometer regions, in directions perpendicular to an external initializing field. This technique can be tailored to produce a wide variety of magnetic-field profiles on nanometer scales with the option of applying electric fields, for example, to move a quantum dot between regions where the magnetic-field direction or strength is different as proposed and demonstrated by the experiments of Pioro-Ladrière et al.12,13 We have fabricated one such design in permalloy and confirmed the accuracy of the modeling by measuring the fields using electron holography.

Figure 1a is a bright-field transmission electron microscopy (TEM) image of a nanomagnetic element design. Once initialized using an applied field \( \mathbf{B}_0 \) in the direction indicated, the magnetization state at remanence (i.e., that which remains once the applied field, \( \mathbf{B} \) is reduced to zero) that the nanomagnets adopt follows the curved arrows. The elements in Figure 1a are designed to produce, in the gaps between the elements, an in-plane stray-field compo-
By perpendicular to \( B_0 \). A plot of the simulated magnetic field, \( B_y \), perpendicular to \( B_0 \), as a function of position along the dashed line in (a). Because of symmetry the field perpendicular to \( B_y \) is negligible, < 2 mT.

To validate the modeling and fabrication, the magnetic field produced by a set of permalloy elements was measured using electron holography (EH),22,23 a transmission electron-microscopy (TEM) technique depicted schematically in Figure 2a. The difference in phase shift between a vacuum reference wave and another part of the same electron wave that has passed through the specimen is used to determine information regarding the magnetic field of the specimen through which the electrons have passed. The gradient of the measured phase shift is an integral of the in-plane component of the magnetic field along the path of the electron beam, and additional techniques are required to deduce three-dimensional magnetic-field information from this data. The TEM-imaged devices were fabricated on 50 nm thick SiN membranes from Agar Scientific. A double-layer PMMA resist was exposed with a Leica Vectorbeam UHR electron-beam lithography system. The thermally evaporated metal consisted of a 100 nm layer of permalloy (Ni80Fe20) capped with a 3 nm layer of Au. EH measurements used a Philips CM300 field-emission-gun TEM, operated at 300 kV. Holograms were acquired at remanence after saturating the sample parallel or antiparallel to the sample length with a field of \( \sim 2 \) T.

Figure 2b is a cosine-contour plot of the measured EH phase shift in a region between the elements shown in Figure 1a. (A cosine-contour plot is obtained by plotting \( \phi' = \cos(\alpha \phi) \), where \( \phi \) is the phase shift and \( \alpha \) a constant “amplification” factor.) The contours indicate regions of equal phase shift, separated from each other by equal amounts of magnetic flux and are analogous to magnetic field lines. It can clearly be seen that a region of uniform magnetic field is indeed present midway between the fingers, and that this field is perpendicular to \( B_0 \). To determine the magnitude of this field, fitting of the EH phase-shift data to a nanomagnetic simulation is required.

Previous techniques for extracting quantitative information from EH data usually either made simplifying assumptions, such as that the magnetic field is distributed uniformly throughout the sample thickness and exists nowhere else, an approximation that can be justified only for very thin
films where the out-of-plane anisotropy forces the magnetization state to lie in the plane, or were obtained from multiple holograms at different specimen tilt angles, composing a three-dimensional picture of the field in the region of interest.\textsuperscript{24}

In the technique presented here, the nanomagnets are modeled using Oommf\textsuperscript{25} or the commercially available LLG\textsuperscript{26} package and the EH phase shift, calculated at each point in the image plane, is then compared with the measured values using the thickness of the magnetic material as the fitting parameter. Additionally Oommf was used for optimizing the device design and for the prediction of magnetic field profiles, such as the data presented in Figure 1b. While the thickness of the evaporated permalloy was 100 nm, oxidation or degradation may decrease the effective magnetic thickness of the film from the ideal case. The magnetic thickness that gives the best simulated fit to the measurements will thus be less than the actual thickness. Once a realistic model that reproduces the two-dimensional EH phase shift has been found, one can be confident that the three-dimensional field distribution predicted by the model will accurately represent that of the device being imaged. The best-fit thickness for the measured device is found to be 55 nm. Figure 2c shows a cosine-contour plot calculated for 62 nm thickness. The simulated contours closely reproduce those measured (Figure 2b). Figure 2d shows measured and simulated (for 55 nm thickness) phase shifts along the center-line of the fingers in Figure 2b. These lines are almost indistinguishable between the fingers, indicating that our models faithfully reproduce the experiment. We can now calculate the stray field produced at any point in three-dimensional space by our nanomagnetic elements.

Figure 2e plots magnetic field along the center-line of the sample in Figure 2b, both directly between, and 100 nm below, the sample. This latter plot is useful in determining the field obtainable in a two-dimensional electron gas (2DEG), for magnetic elements patterned on top of a typical GaAs/AlGaAs heterostructure, commonly used in quantum electronics. It can be seen that the reduction in field strength at this depth is moderate; this is also a necessity in schemes such as those in Figure 1a where magnetic fields must be applied to layered structures and Barnes\textsuperscript{28} where a local field extends down to passing quantum dots which form spin qubits.

Previous measurements of patterned discs and pillars in dysprosium\textsuperscript{7,8} produced fields of up to 400 mT but involved just the out-of-plane component of the magnetic field. The effect of the Dy magnets in the work of Ye et al.\textsuperscript{9} was the addition of a periodic magnetic field parallel to the applied field with an amplitude in the underlying 2DEG of $\sim$10 mT. However, dysprosium is only suitable for single-field directions due to its large coercive field. Larger magnetic stripes and rectangular shapes have also been measured,\textsuperscript{10,11} producing out-of-plane fields in the 2DEG of up to 500 mT; however, the elements used had in-plane dimensions of tens to hundreds of micrometers and produced fields over extended rather than localized regions.

Permalloy is a magnetically soft material and for a given element will produce a smaller maximum field. However, the small coercive field allows the magnetization to realign, giving the transverse fields of Figure 1b. Harder materials such as cobalt can produce larger fields\textsuperscript{10} and so are good choices where fields parallel to an initializing field are required. However, in our simulations with cobalt, the magnetization was not fully aligned to the curved fingers when the initializing field was removed and consequently these elements gave smaller transverse fields. Some other materials may be suitable; in our simulations, iron was found to give $\sim$1.6 times the field of permalloy but with less good confinement.

The magnetic structures presented here produce an in-plane field at remanence that is chosen to be perpendicular to the field used for initialization. The field is concentrated in an area $\sim$0.5 $\mu$m\textsuperscript{2}, and oscillates with an in-plane peak-to-peak amplitude of $\sim$90 mT between the magnets and $\sim$60 mT at the depth of a typical 2DEG. Unwanted stray fields outside this region are minimal, as most of the magnetic flux is channelled from one magnetic element to the next; this type of stray-field control may be of great benefit in spintronic devices and is a capability that has not previously been explored.

Figure 3a, b show nanomagnetic elements capable of producing fields in multiple in-plane directions using a single reversible applied field. Figure 3c shows the effect of polarizing such elements and then gradually applying a reverse field. The central broad sections of elements such as those in Figure 1a are less anisotropic than the fingers and so allow for selective reversal of the magnetization of specific elements. Elements with continuous fingers that are not joined to form a “body” region, such as those in Figure 3a, require a larger coercive field to switch their magnetization; compare the elements in Figure 3c (ii and iii) at 40 mT. The solid sections of the S-shaped elements reverse easily from “E” to “W” polarization and are then stable to higher fields, whereas the finger regions resist depolarisation, allowing E and W regions to coexist; Figure 3b. Being able to switch different elements at different fields allows greater control in designing magnetic profiles. Figure 3d shows in cross-section how existing split-gate technology can be used to vary the field direction electrically. Applying different voltages to the asymmetrically placed electrostatic gates shifts the potential minimum defining a channel or quantum dot to produce a 90° rotation of the local field. Figure 3e shows a different style of element used to create a stronger out-of-plane field. It too is initialized with an in-plane field and produces fields $>$80 mT over an area of 0.5 $\mu$m\textsuperscript{2} 100 nm below the plane of the magnets. Inter-
can be confined to desired submicrometer regions and
of a single global initialization field. The stray field produced
directions in the absence of an applied field, through the use
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roughly equal to the gap width
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\( \sim \)

FIGURE 3. (a,b) Schematic nanomagnetic elements used to create
fields in multiple directions N, S, E, and W from a single reversible
field \( B_0 \). (b) Field at W is produced by an initial \( B_0 \) followed by
smaller reverse field \( B'_0 \). (c) Simulated sections of (a and b) at
different reverse fields \( B'_0 \). Elements initially saturated at \( B_0 \). Color
represents magnetic direction as shown. The higher coercive
fields of narrow slotted sections allows selective switching. By
representing magnetic direction as shown. The higher coercive
field strength. All scale bars are 500 nm.

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REFERENCES AND NOTES

mediate field directions can be produced by variations on
these designs.

Larger fields may also be achieved by improved align-
ment of the magnetization in the fingers, a reduction in
the gap between fingers or an increased thickness of
deposited material. Our simulations predict that fields
greater than 200 mT are possible with other materials,
such as iron, using geometries similar to those shown
here. Empirically, for simulated elements of thickness
\( T \) and gap width \( G \), the field \( B \) is given by
\( B(\text{mT}) = m \times (T/G) + c \), where \( m \) is a constant and \( c \) is an offset, with
\( m, c = (450, -11) \) for Fe and \( (230, 3) \) for permalloy. This
holds for thicknesses up to \( \sim 120 \) nm (above which flux-
closure domains form within the elements), and for gap
widths above \( \sim 500 \) nm (Fe) and \( \sim 120 \) nm (permalloy).
This indicates that the flux spreads vertically over a region
roughly equal to the gap width \( G \).

In conclusion, the nanomagnets presented here can
produce controlled local magnetic fields in multiple arbitrary
directions in the absence of an applied field, through the use
of a single global initialization field. The stray field produced
can be confined to desired submicrometer regions and
electrostatic gates used to move electrons between regions
of different magnetic direction and field strength. The ease
with which this design can be tailored to produce arbitrary
field profiles and the possibility of electrostatic and magnetic
gate integration mean this work may be useful in a wide
range of spintronic and nanoelectromechanical applications,
or anywhere localized fields or field gradients\(^2\) are required.

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