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Time resolved imaging of magnetization dynamics in hard disk writer yokes excited by bipolar current pulses

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A partially built hard disk writer structure with a NiFe/CoFe/Ru/NiFe/CoFe synthetic antiferromagnetic (SAF) yoke was studied by time and vector resolved scanning Kerr microscopy. All three time dependent components of the magnetization were recorded simultaneously as a bipolar current pulse with 1 MHz repetition rate was delivered to the coil. The component of magnetization parallel to the symmetry axis of the yoke was compared at the pole and above a coil winding in the centre of the yoke. The two responses are in phase as the pulse rises, but the pole piece lags the yoke as the pulse falls. The Kerr signal is smaller within the yoke than within the confluence region during pulse cycling. This suggests funneling of flux into the confluence region. Dynamic images acquired at different time delays showed that the relaxation is faster in the centre of the yoke than in the confluence region, perhaps due to the different magnetic anisotropy in these regions. Although the SAF yoke is designed to support a single domain to aid flux conduction, no obvious flux beaming was observed, suggesting the presence of a more complicated domain structure. The SAF yoke writer hence provides relatively poor flux conduction but good control of rise time compared to single layer and multi-layered yokes studied previously. [http://dx.doi.org/10.1063/1.4865887]

Increased data rates in perpendicular magnetic recording[1] (PMR) require the magnetization within the recording head to respond to the driving field sufficiently quickly that erase after write[2] (EAW) phenomena are avoided. Previous studies[3–9] have addressed the rise time and remnant value of the write field at the pole tip. However, magnetic flux[10] is delivered to the confluence and tip regions from the yoke by a process known as "flux beaming." Therefore, improved understanding of the dynamics within the yoke and their effect upon the write field are needed to optimize writer design. Kasiraj *et al.*[11] made the first observations of flux beaming in a yoke with a closure domain structure by scanning Kerr microscopy, confirming that flux conduction occurs by magnetization rotation near the center of the yoke with little or no magnetization rotation near the edges. Increased driving frequency led to greater confinement of the flux near the center of the yoke, while increased driving amplitude caused the flux to spread due to increased domain wall displacement. The increased availability of mode-locked pulsed laser systems of improved mode profile has allowed time resolved measurements to be performed with diffraction limited spatial resolution and picosecond temporal resolution. In recent studies[12–14] we have shown that yokes with different coil configurations can occupy different meta-stable states during pulse cycling. Pulses of similar amplitude but opposite polarity also caused the pole tip magnetization to exhibit changes of different amplitude, suggesting a complicated influence of the yoke dynamics upon the write field. All of these studies were carried out with unipolar pulses, while a hard disk drive employs a bipolar waveform with positive and negative phases of similar amplitude.[9] Therefore in this study, to afford more direct comparison with performance of the writer in a hard disk drive, bipolar pulses have been used in time resolved scanning Kerr microscopy[15] measurements performed on a partially built writer with a NiFe/CoFe(100 nm)/Ru/NiFe/CoFe(100 nm) synthetic antiferromagnetic (SAF) yoke structure.

A schematic of the writer geometry and TRSKM setup is shown in Figure 1. The writer geometry is the same as in Ref. 12 except that the bridge length is 1 μm in the present case. There are three coil windings beneath the yoke (C1, C2, and C3) and time resolved signals were acquired at the three positions A, B, and C. Position A lies deep in the confluence region, B lies on the symmetry axis of the yoke at the edge of the confluence region, while C lies at the intersection of the symmetry axis and coil C2.

A Ti: Sapphire mode locked laser generated 800 nm wavelength pulses at a repetition rate of 80 MHz that was reduced to 1 MHz by a pulse picker. The laser pulses then passed through a 50/50 non-polarizing beam splitter (BS), before being focused by a $\times$60 objective lens onto the surface of the sample, which was mounted on a piezoelectric scanning stage. The back-reflected beam was directed by the beam splitter into a quadrant photo-diode optical bridge detector[16] designed to sense all 3 components of the vector

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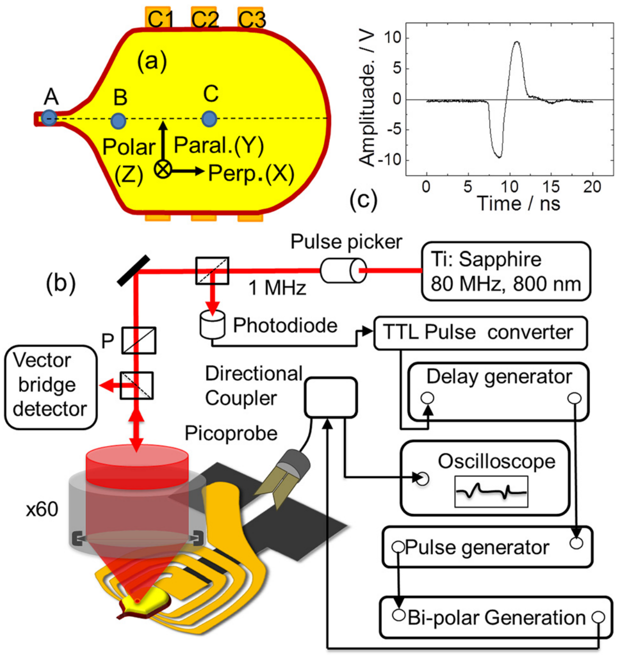

FIG. 1. (a) Sketch of the device and three positions where time resolved signals were acquired: A, deep in the tip region; B, on the symmetry axis and at the edge of the confluence region; and C, at the intersection of the symmetry axis and the C2 coil. The three components of the magnetization are labelled perpendicular (X), parallel (Y), and polar (Z). (b) The time resolved scanning microscopy setup. (c) The bipolar pulse delivered to the coil.

magnetization simultaneously. Due to the optical skin effect, only the top (∼20 nm) of the device is sensed. The labeling of the signals is consistent with previous works, with orientations being specified relative to the expected direction of the static magnetization in the vertical direction (Y) in Figure 1(a). The output signals from the bridge were input to 3 lock-in amplifiers that yielded the change in each magnetization component induced by the electronic pulses. A 3.14 KHz square wave was used to apply amplitude modulation to the electronic drive waveform and as the reference for the lock-in amplifiers.

A beam splitter placed immediately after the pulse picker was used to direct part of each laser pulse onto a fast photo diode, the output of which was passed through transistor-transistor logic (TTL) pulse converter and used to trigger a computer-controlled digital delay generator. The TTL output of the delay generator was in turn used to trigger a pulse generator capable of producing unipolar pulses of 2 ns duration and amplitude of up to 40 V. A combination of two power dividers, a polarity switcher, and some cables of carefully selected length were used to convert the unipolar output of the pulse generator into a bi-polar pulse. The resulting bi-polar pulse was delivered to the writer coil through a directional coupler, so that the reflected pulse could be monitored by a 50 GHz sampling oscilloscope. The pulse directed into the coil had ∼20 V (p-p) amplitude as shown in Figure 1(c). The time delay between the delivery of the electronic pulse and the arrival of the laser pulse at the sample surface was controlled by adjusting the setting of the delay generator.

Figure 2(a) shows the normalized perpendicular (X) component of the dynamic magnetization at positions A, B,

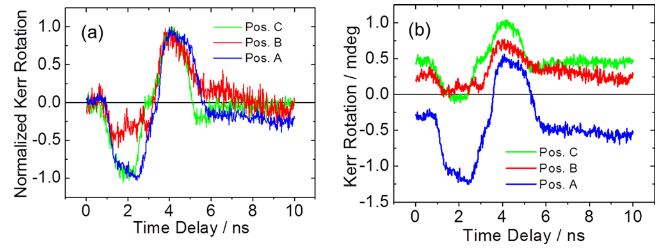

FIG. 2. (a) The normalized perpendicular (X) magnetization component at position A, B, and C. An offset was subtracted prior to normalization. (b) The signals in (a) prior to offset subtraction and normalization.

and C. An offset was subtracted prior to normalization so that the rise and fall times may be more easily compared. The dashed line shows the normalized driving current recorded by the oscilloscope. Figure 2(b) shows the same signal as in Figure 2(a) but without the normalization and offset subtraction. Unsurprisingly, since position C is directly above the center coil, of the 3 positions, the magnetization dynamics at C follow the driving current most closely. In fact the normalized driving current and signal from position C are closely overlapped except between 4.5 and 5.5 ns, where the signal at C leads the driving current, and at 5.5 ns where the signal overshoots the driving current. These differences are possibly the result of secondary pulses caused by impedance mismatches between the writer coil, a long coplanar strip structure running from the device to the edge of the wafer, and the high frequency probe that provides a transition to coaxial cable. The shape of the normalized time resolved signal at position A is similar to that at C, following it closely when the driving pulse is rising, but then lagging behind on the falling edge. This suggests that the yoke dynamics only dominate the dynamics within the pole tip, and hence the write field, when the driving pulse is rising. The signal obtained at position B has smaller amplitude. While the magnetic field generated by the coil lies in the plane of the yoke at position C, it is canted out of plane at position B, and so a smaller in-plane deflection of the magnetization is to be expected. A larger signal is obtained at A due to the concentration of flux in the confluence region as intended. The signal at A has a negative offset while those from B and C have positive offsets suggesting that full relaxation is not achieved within 1 μs and has different character at different positions within the writer. The signal at position A also shows a response of different amplitude for different polarities of the driving current. This asymmetry is consistent with results from Ref. 14, in which a writer was tested separately with unipolar pulses of opposite polarity.

In order to obtain a better understanding of the dynamics in the writer, the time resolved images in Figure 3 were acquired at delay times corresponding to points of interest in the perpendicular channel signal from position C, which is shown in Figure 3(b). The borders of the yoke have been highlighted so as to guide the eye.

The synthetic antiferromagnetic yoke structure was intended to produce a single domain static ground state. However, during pulse cycling, the yoke can also occupy a meta-stable equilibrium state depending upon the driving pulse configuration.[13,14] The dynamic images suggest the

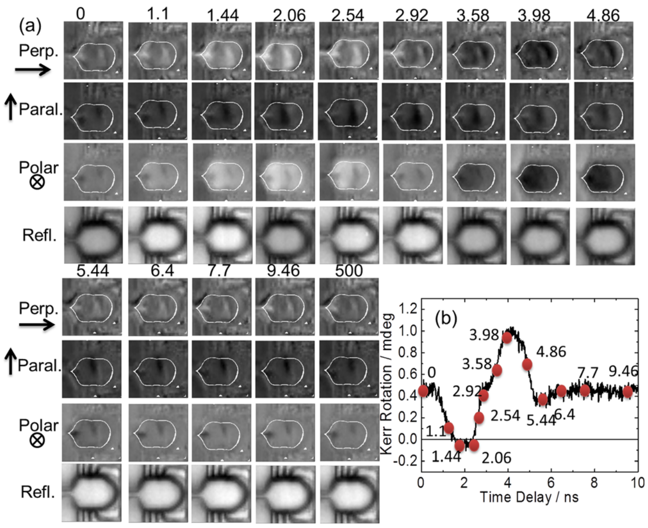

FIG. 3. (a) Dynamic magnetization and reflectivity images acquired at the delay times indicated in panel (b). For a particular channel, the contrast is normalized to the maximum Kerr amplitude observed within that time series. Black/white corresponds to the dynamic magnetization lying in the −/+ z-direction, −/+ x-direction, and +/− y-direction for the polar, perpendicular, and parallel channels, respectively. The Cartesian axes are defined within Figure 1(a) and shown next to the row names in (a). (b) Time dependence of perpendicular (X) component measured at position C in Figure 1(a).

formation a multi-domain equilibrium state. The perpendicular channel images reveal a light vertical stripe close to winding C3 up to 3.58 ns delay, after which additional black contrast appears around the stripe before quickly fading again. The parallel channel images also show a black stripe at a similar but not quite identical position that expands and then contracts again with increasing time. The polar channel images show similar, but again not identical, features to the parallel channel, supporting the idea that the yoke is sufficiently thick that the magnetization can cant out of plane to some extent in a truly 3 dimensional magnetization distribution. In addition, there is a more uniform variation in contrast superimposed when the pulse is present. The field generated by the coil should favor contrast of opposite sign at opposite ends of the writer, but this is not observed, in agreement with previous studies.[14]

Within the confluence region, a light strip is observed along the symmetry axis within the perpendicular images for delay times in the range of 0–2.92 ns, and 5.44–500 ns, confirming the concentration or funneling of flux within this region. In fact, the images change very little between 5.44 ns and 500 ns, indicating that the writer relaxes to a state of metastable equilibrium at 5.44 ns, in agreement with the offset of the signal at position A observed in Figure 2(b). The incomplete relaxation within the confluence region could occur for one of two reasons. First, the effective anisotropy within this area may be different to that within the main part of the yoke, due to the shape or stress or both. If the easy axis is canted from the parallel (Y) direction, then the magnetization may switch between 2 states that have inequivalent perpendicular components of magnetization. Second, due to the funneling effect, the magnetization in the confluence region is more sensitive to any residual flux present in other regions of the yoke. Compared to Refs. 13 and 14, in which contrast in the perpendicular channel was observed in either the upper or lower half of a multilayered yoke but not both, the contrast within the perpendicular (X) channel images at peak values of the driving field (1.44 and 3.98 ns) is more uniform across the width of the yoke. Even so, flux beaming is not observed in the region of the coil windings. This may be because the constituent layers of the SAF yoke have thickness greater than the exchange length, leading to a more complicated 3 dimensional ground state that cannot be probed optically.

Time resolved scanning Kerr microscopy has been used to study the writer dynamics excited by a bipolar current pulse. Time resolved measurements of the perpendicular (X) magnetization component show that the yoke only dominates the dynamics within the confluence region when the pulse is rising. The amplitude of the signal from position A, which is deep within the confluence region, is much larger than those from other positions, indicating the funneling of the flux from the yoke to the tip. Dynamic images show an incomplete relaxation behavior within the confluence region after the pulse has gone, which may be due to modified anisotropy within this region and funneling of residual flux from other parts of the yoke. In-plane dynamic images reveal the existence of a non-uniform equilibrium state during pulse cycling and an absence of flux beaming, suggesting that the SAF yoke, which is thick compared to the exchange length, may occupy a more complicated 3 dimensional equilibrium state that cannot be probed optically.

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