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Effects of combined current injection and laser irradiation on Permalloy microwire switching

J. H. Franken,[1,2] P. Möhrke,[1] M. Kläui,[1,a)] J. Rhensius,[1,3] L. J. Heyderman,[3] J.-U. Thiele,[4]
H. J. M. Swagten,[2] U. J. Gibson,[5] and U. Rüdiger[1]
[1]*Fachbereich Physik, Universität Konstanz, Universitätsstr. 10, 78457 Konstanz, Germany*
[2]*Department of Applied Physics, Eindhoven University of Technology, Den Dolech 2, 5600 MB Eindhoven, The Netherlands*
[3]*Laboratory for Micro- and Nanotechnology, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland*
[4]*Hitachi Global Storage Technologies, San Jose Research Center, 3403 Yerba Buena Road, San Jose, California 95135, USA*
[5]*Thayer School of Engineering at Dartmouth, 8000 Cummings Hall, Hanover, New Hampshire 03755-8000, USA*

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Combined field- and current-induced domain wall (DW) motion in Permalloy microwires is studied using fast magneto-optical Kerr-microscopy. On increasing the current density, we find a decrease of Kerr signal contrast, corresponding to a reduction in the magnetization, which is attributed to Joule heating of the sample. Resistance measurements on samples with varying substrates confirm that the Curie temperature is reached when the magneto-optical contrast vanishes and reveal the importance of the heat flow into the substrate. By tuning the laser power, DWs can be pinned in the laser spot, which can thus act as a flexible pinning site for DW devices. © *2009 American Institute of Physics*. [doi:10.1063/1.3265944]

Recently, the feasibility of moving magnetic domain walls (DWs) through a nanowire by a spin polarized current has been demonstrated by a number of groups.[1,2] For applications, one of the most challenging problems is still the very high current density required to move a DW, causing significant Joule heating. This can dramatically alter the DW motion, for instance due to the associated reduction of the saturation magnetization M_s, if the temperature approaches the Curie temperature T_C. Heating up to T_C by current pulses has been demonstrated before through indirect temperature measurements and the observation of the formation of multidomain states in small magnetic wires.[3–5] However, a real-time measurement of the magnetization during injection of current pulses has not yet been reported, which would be necessary to better correlate the pulse injection and heating effects. In order to reduce this heating, one first needs to gain an understanding of the influence of different substrate materials or differently thick electrically insulating interlayers between nanowire and substrate. This has already been analyzed by theoretical calculations,[6] but so far systematic studies which investigate the paths of heat transfer are lacking. Such studies are essential to clarify whether the heat flows primarily vertically into the substrate or along the metal nanowire into the contacts and would lead the way to tailored substrate materials or different sample/device design.

Apart from the current-induced Joule heating of the wire, the introduction of controllable pinning sites for DWs is of major importance for applications. For this purpose geometrical constrictions are commonly used to pin the DW at a specific position.[7] However, their pinning strength and position cannot be altered after fabrication. In particular for logic applications, flexible pinning would be key for generating logic gates with variable functionality.

In this letter, direct real-time measurements of the decrease of the magnetization with increasing current density in Permalloy microwires using a dynamic Kerr-microscope are presented. The temperature of the microwires is estimated from the wire resistance during the application of a current pulse. It is found that the magnetization drops during the current pulse when reaching a critical current density, suggesting that Joule heating is crucial for DW motion. A comparison of identical wires on different substrates indicates that the thickness of the insulating oxide layer has a large impact on the temperature rise. By tuning the laser power, we can reproducibly pin a DW locally in the laser spot, opening a way to generate flexible pinning sites.

Measurements are conducted at room temperature using a time-resolved magneto optical Kerr effect (MOKE) magnetometer as outlined in Ref. 8. For the current study, a differential detection scheme with a polarizing beam splitter and two detectors is used to increase the signal contrast. The magnetization is probed in a region of ~1 μm diameter on the sample determined by the size of the focused laser spot [Fig. 1(a)]. An argon-ion laser operating at variable output power up to 0.2 W with a wavelength of 488 nm was used.

The structures studied are 1.5 μm wide, 20 nm thick Permalloy ($Ni_{80}Fe_{20}$) wires doped with 2% Ho, which sets the damping parameter α.[9] The wires have a zig-zag geometry, which allows for controlled nucleation of a head-to-head DW at a bend in the wire.[2] The region probed with the laser spot is located 5 μm to the right of a bend, and a DW at the bend can be moved through the laser spot by field and/or current pulses. The directions of current and field, as well as a DW at the bend are shown in Fig. 1(a). The structures were fabricated using electron-beam lithography, sputtering and lift-off on thermally oxidized Si with a 190 nm-thick oxide layer, and naturally oxidized high-resistance Si with an oxide layer of a few nanometers. The samples were

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[a)] Electronic mail: mathias.klaeui@uni-konstanz.de.

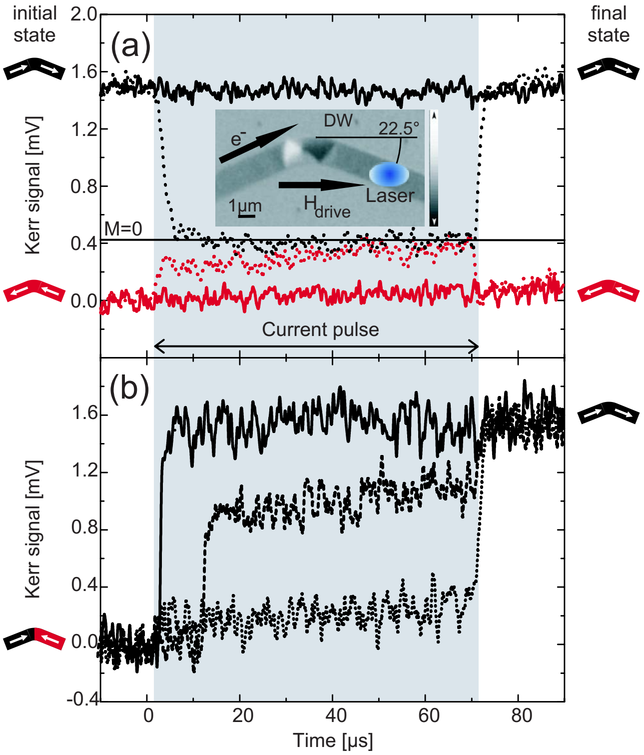

FIG. 1. (Color online) (a) Kerr signals obtained in zero field by current pulses through a wire with the two possible monodomain states, indicated in the schematic drawings. The current densities used are 2.7 and 7.8 $\times 10^{11}$ Am^{-2} for the continuous and dotted lines, respectively. The inset shows the experimental geometry (for details see Ref. 8). (b) Kerr signals from single shots of combined current- and field-induced DW motion for three different current densities. The current densities used are 2.7, 6.2, and 7.8×10^{11} Am^{-2} for the continuous, dashed, and dotted line, respectively. The dc bias field is 8.3, 6.8, and 6.1 G, respectively. The schematic drawings show the magnetic configuration before and after the current pulse.

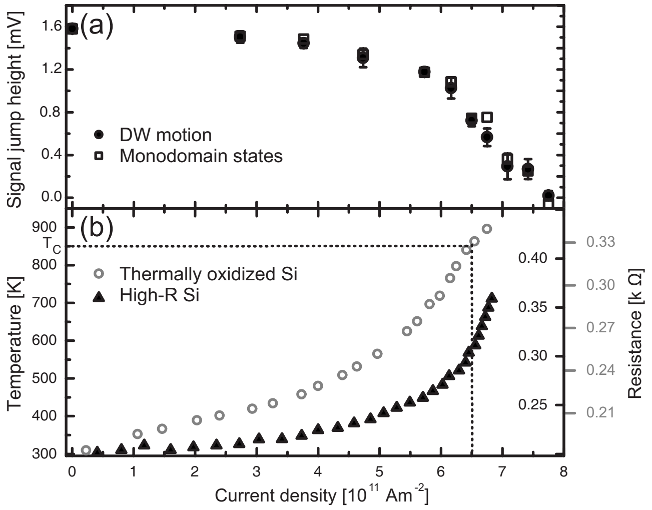

FIG. 2. (a) The difference of the Kerr signal levels of both monodomain states during current pulses (open squares) and Kerr signal jump height of DW motion events as a function of current density (filled circles). The drop indicates a demagnetization due to Joule heating; (b) Resistance (right) and corresponding temperature (left) as a function of current density for Permalloy nanowires on different substrates; thermally oxidized Si (gray circles, ticks outside the ordinate to the right), naturally oxidized high resistance Si (black triangles, ticks inside the ordinate to the right). For the thermally oxidized Si T_C is reached at a current density of 6.4×10^{11} Am^{-2}. Additionally, a reduced Joule heating for the naturally oxidized Si is observed. The different scales originate from slight differences in the wires used.

capped with 2 nm Pd and coated with 60 nm of Ta$_2$O$_5$ to enhance the magneto-optical signal.[10]

To separate the influence of Joule heating on the magnetization and its influence on DW motion, experiments were first conducted on monodomain nanowires on the Si substrate with a 190 nm-thick oxide layer. In order to obtain a monodomain state, the wires are saturated in either of the two possible directions shown in Fig. 1(a), followed by a 70 μs current pulse. In all experiments, the duty cycle and number of repetitions was kept very low in order to ensure that the sample properties do not change due to overheating. Since no DW is present, only the change of magnetization at the laser spot position due to the current is observed [Fig. 1(a)]. For a current density of 7.8×10^{11} Am^{-2}, a decrease or increase in the signal amplitude during the current pulse, depending on whether the magnetization points right or left, is observed. During this pulse, the difference of signal amplitude for the two magnetization states is zero indicating that for both states the wire is completely demagnetized and T_C is reached. For a lower current density of 2.3 $\times 10^{11}$ Am^{-2} no change is observed. The difference of signal amplitude of the two monodomain states during the pulse versus the current density of the pulse is plotted in Fig. 2(a) (open squares). The reduction in the signal difference that can be seen is directly related to a change of M_s. The asymmetry in magnitude of the signal features for both monodomain states does not depend on the direction of the current and occurs because the Fresnel and Kerr component of the light reflected is influenced differently by the heating.

In a second step, single shot MOKE measurements of DW motion are obtained with current pulses of variable amplitude and an additional external magnetic field parallel to the wire to assist in driving the DW. If the current is small and does not cause much heating, a single jump is expected when the DW crosses the spot position and the magnetization changes sign. This is indeed observed in Fig. 1(b) for the lowest current density ($j=2.7 \times 10^{11}$ Am^{-2}).

If at higher current densities the wire is heated to a temperature close to T_C, one expects a more complex magnetization trace consisting of three jumps. The first jump occurs at the beginning of the pulse (t_0) because of a reduction of M_s by the increased temperature. The second jump at t_{DW} corresponds to DW motion which reverses the sign of M at the spot position. The third jump at the end of the pulse (t_{F}) corresponds to an increase in M_s because the wire cools down. Experimentally, such features are observed. For $j=6.2 \times 10^{11}$ Am^{-2}, a DW jump is observed at $t_{\mathrm{DW}}=12$ μs and also a cooling jump at $t_{\mathrm{F}}=70$ μs is visible. The expected jump at t_0 is much smaller than the one at t_{F} due to the asymmetry of the amplitude change. For $j=7.8 \times 10^{11}$ Am^{-2} the two jumps due to heating and cooling are large enough to be visible but no DW motion jump is observed at all. This means that the magnetization does not reverse by DW motion and can be explained by the temperature approaching T_C such that M_s vanishes almost completely and an incoherent gradual reversal takes place.

The loss of magnetization as a function of current density is seen again in the decrease in the magnitude of the DW jump at t_{DW} and is shown quantitatively in Fig. 2(a) (filled circles). The average of five individual events was used for each data point. At 7.8×10^{11} Am^{-2} the contrast vanishes completely indicating once again that the structure has reached T_C (850 K for Permalloy[11]). This current density is

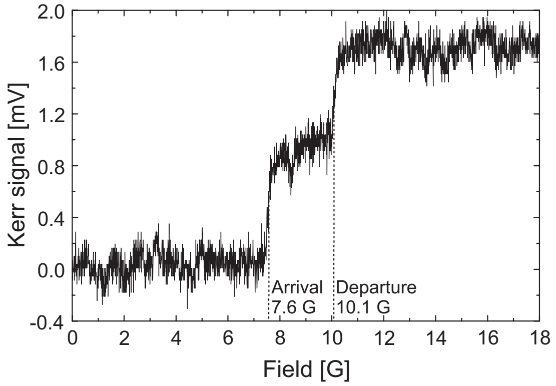

FIG. 3. MOKE trace showing the pinning of a DW in the laser spot. The field sweep rate is 350 kG/s and the wall was pinned between 7.6 and 10.1 G.

lower than the critical current density for pure current induced DW motion.

In order to obtain the temperature of the structure as a function of the injected current, the resistance was measured as a function of current density [circles in Fig. 2(b)]. Above the highest current density shown, the microwires were destroyed, which was accompanied by a sharp change in resistance and probably related to electromigration. Lock-in measurements of the resistance of a set of four wires in the range 50–350 K yielded a linear increase. The structure is stable in this temperature range, as the Pd capping layer prevents oxidation by the Ta_2O_5 (magneto-optical enhancement layer) and the SiO_2 is very inert. The result indicates that T_C is reached at a current density of $(6.4 \pm 0.9) \times 10^{11}$ Am^{-2}. This current density is lower than the one at which the MOKE contrast was lost, which might be attributed to overestimating the temperature by assuming a purely linear dependence of current density and resistance.

For comparison, the same temperature measurement was conducted on almost identical wires on a high-resistance silicon substrate with just the native oxide layer [see Fig. 2(b) (triangles)]. Here the temperature during current injection is significantly lower, which can be attributed to a better heat conduction of the substrate as theoretically predicted.[6] Nevertheless, this sample design was not suitable for magneto-optical measurements, because laser-induced photo carriers in the substrate shunt the injected current. With the laser off even at elevated temperatures no significant dark current can be observed. However, the temperature of the wire during current injection still reaches more than half the Curie temperature and electrically insulating materials with even higher heat conductivity are needed. This is particularly important since these results show that a significant amount of heat is transferred perpendicular to the current direction into the substrate and not along the wire into the contacts.

When increasing the laser power we find that the laser spot can act as a pinning site for the DW. In a typical trace in Fig. 3 at 0.12 W laser power, a DW is prepared and the field is ramped up at a sweep rate of 350 kG/s. The DW is depinned from the wire bend and moves to the area covered by the laser spot when the field reaches 7.6 G. It remains there until the field has reached 10.1 G and finally depins (as reflected by the two jumps in the MOKE trace). The field required to depin the wall increases with laser power so that the pinning strength can be tuned flexibly by adjusting the laser. Indeed, during current-induced DW motion, pinning was found frequently at the laser spot at a higher laser power than that used for the previous results in this letter. When the laser was switched off during the current pulse, no pinning at this site could be observed confirming that the pinning is not due to some sample inhomogeneity.

The preference of the DW to remain at the spot with the laser on might be caused by changed magnetic properties such as a locally reduced M_s due to the higher temperature or by spin currents generated by the strong thermal gradient.[12] This effect has not been reported before and opens up a way to actively control DW pinning i.e., both position and strength, which could be useful for future device studies.

In conclusion, using real-time MOKE we have observed demagnetization in Permalloy microwires with increasing current density leading to a decrease of signal contrast of combined field/current-driven DW events. Due to the limited heat conduction of the Si substrate with a thick oxide layer, the sample is already demagnetized for current densities below the critical current density for DW motion and temperature measurements indicate that the Curie temperature is reached. For naturally oxidized Si substrates, a reduced heating was observed. Therefore both for experiments and potential applications, electrically insulating materials with high heat conduction are crucial for keeping nanostructures at low temperatures to ensure a high efficiency of spin transfer torque and long lifetimes for device applications. Furthermore, we have shown that local laser-induced heating can be employed for generating tunable DW pinning sites.

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