Near-field magneto-optical imaging in scanning tunneling microscopy

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Images of magnetic bits written in a Pt/Co multilayer are presented. Using photosensitive semiconducting tips in a scanning tunneling microscope, both surface topography as well as polarization-dependent optical transmission are measured. Magnetic contrast is achieved by detection of the Faraday effect. Magneto-optical lateral resolution of 250 nm is demonstrated. © 1995 American Institute of Physics.

In the field of scanning probe microscopies the measurement of magnetic structure with submicrometer down to ångström resolution has become an important issue. Several techniques are being explored and improved to obtain high-resolution magnetic imaging; detection of magnetic stray field by magnetic force microscopy1 or a Hall probe,2 spin-polarized tunneling using a magnetic tip,3 near-field magneto-optics,4,5 where a subwavelength aperture or probe is used to locally detect the interaction of polarized light with a magnetic sample,4,5 and tunneling-excited emission of polarized photons.6 Growing attention is being paid to the use of optical interactions, in which case the scanning probe can be nonmagnetic and thus nonintrusive. In this category we recently introduced a new technique for magnetic imaging, using photosensitive semiconductor tips in a scanning tunneling microscope (STM).7 It has been shown that semiconductor tips can yield atomic resolution,8,9 and that they can be used as sensitive photodetectors both in a tunneling7,9 as well as in an atomic force microscope.10 The detection is based on separation of photoexcited electron-hole pairs by the depletion field, creating a surface photovoltage and the possibility to draw a zero-bias photocurrent. We exploit this photosensitivity to locally detect Faraday ellipticity or magnetic circular dichroism (MCD) of a ferromagnetic sample. MCD will lead to a different optical transmission through the sample for light of right versus left circular polarization. Modulating the light polarization, the resulting tunnel current modulation has allowed us to measure hysteresis loops of a Pt/Co multilayer.7 In this letter we will present images of magnetic bits thermomagnetically written in a Pt/Co multilayer, and demonstrate for the first time that subwavelength lateral resolution can be achieved when using a semiconductor tip as a local photodetector in a scanning tunneling microscope.

The experiments were performed in an STM at ambient temperature and pressure. The semiconductor tips were illuminated along the tip axis through a semitransparent sample. A linearly polarized HeNe laser beam (633 nm) was guided through a Pockels cell and a polarizer, which provided an intensity modulation (IM) of a few percent at 80 kHz. Next the beam passed through a photoelastic modulator, introducing a 84-kHz sinusoidal polarization modulation (PM) between right- and left-handed circular polarization of the light. Finally, the beam was focused onto the sample by a 30-mm focal length objective, to a spot of 20±5 µm diameter. An external bias voltage was applied to the sample, so as to operate the semiconductor tip in reverse bias. The current was measured by a 100-mV/nA current-to-voltage converter of 100 kHz bandwidth. This signal was led into two lock-in amplifiers for phase-sensitive detection of the current modulations. The bandwidth of the STM constant-current regulation system was 2 kHz. At every point of the scan the topographical height was recorded simultaneously with the current modulations at 80 and 84 kHz. The intensity modulation signal served to determine the optical response of the tip R, being the ratio of the detected relative tunnel current modulation ∆I/∆P with respect to the preset relative modulation of incident optical power ∆P/P. The calibrated polarization modulation signal is ∆I/∆P divided by the response R and multiplied by √2 to account for the rms value of sinusoidal modulation. In order to be consistent with the definition of Faraday ellipticity11 the circular dichroism signal (CD) is the calibrated PM signal divided by a factor of 2.

The GaAs tips were prepared by cleaving (001) wafers along (110) and (110) directions, forming a corner bounded by these planes. The GaAs was p-type of 10¹⁷ cm⁻³ doping density. Inspection by scanning electron microscopy (SEM) and STM showed that cleavage produced well-defined corners with tip apex radii of approximately 100 nm. We extensively characterized the tips by measuring current versus voltage curves with and without illumination.9 While scanning we carefully followed the tip behavior by monitoring the quality of the topographical images and the stability of the response R. The Pt/Co multilayer consists of a 6 Å Pt base layer and 20 pairs of 3.5 Å Co and 6 Å Pt layers evaporated on a glass substrate.12 In Fig. 1 a topographic scan of the Pt/Co multilayer is shown, recorded with an illuminated GaAs tip. The characteristic microcristallites of 10 to 20 nm diameter originate from the pillar-wise growth of the multilayer. The sample exhibits perpendicular magnetic anisotropy and was homogeneously magnetized except for rows of thermomagnetically written bits of opposite magnetization. Writing was accomplished in a field of 25 kA/m by

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locally heating the Pt/Co multilayer with a 488-nm Ar\textsuperscript{+} laser beam focused onto the sample by a microscope objective. The bits have a diameter of 0.8±0.2 \, \mu m and are spaced 2.0±0.1 \, \mu m apart within the rows. The rows are separated by a distance of 2 to 3 \, \mu m.

When irradiating a semiconductor tip with modulated light intensity a modulation of current can be detected due to the creation of photocarriers and due to heating effects\textsuperscript{13}. The photocarriers can cause a direct current through the tunnel barrier as well as a displacement current through the stray capacitance between tip and sample. The displacement current is due to the modulation of surface photovoltage on the irradiated part of the tip. In the following measurements the signals due to displacement current were more than ten times smaller than the signals measured while tunneling. We have corrected for the displacement current by subtracting the modulation offset measured when the tip was out of tunneling range.

Phase-sensitive detection of the two components of intensity modulation versus incident laser power has been depicted in Fig. 2. The in-phase response shows a steep increase for low power and flattens off at higher power. This saturation behavior is characteristic for the gradual transition from photoamperic (small tip-sample distance) to photovoltaic (large tip-sample distance) regime, which can be understood from a simple one-dimensional current transport model of metal-insulator-semiconductor devices\textsuperscript{7}. We attribute the in-phase component to the photocarrier current. The out-of-phase component shows a quasilinear relation with power. This is attributed to the tip-sample distance modulation as a consequence of periodic thermal expansion of tip and sample. We verified that both the phase and curve shape of the heating effect compare well with a similar measurement using a metallic tip.

Figure 3 demonstrates the magneto-optical imaging capabilities of our semiconductor tips. To assure that heating effects were negligible in the modulation signals, we detected the in-phase components and chose the light intensity such that the out-of-phase component remained less than 15\% of the in-phase component. Figure 3(a) shows a 6.0×3.6 \, \mu m\textsuperscript{2} image of the magnetic bits, taken in 8 min time. In this image the bits were written in rows from bottom to top. Indeed, we observe that in this direction the interbit distance is approximately 2 \, \mu m. Outside the area with the bits a CD signal with uniform sign has been observed, whereas on the bits a sign reversal of the CD signal was found. In a previous paper we demonstrated that upon reversal of the magnetization of a Pt/Co multilayer a sign reversal of CD can be observed in an STM due to Faraday ellipticity\textsuperscript{7}. Thus the observation of a sign reversal is in agreement with the fact that the bits have opposite magnetization with respect to the rest of the sample. Further details are given in Figs. 3(b)–3(d), showing the simultaneously measured topography, response \( R \), and CD signal on a line scan over the two topmost bits of Fig. 3(a). The fine structure on the topographic signal is due to the presence of microcrystallites, as has been shown in Fig. 1. Note that the scales for the topographic corrugation and the lateral coordinate differ by three orders of magnitude.

**FIG. 1.** Topographic 100×50 \, nm\textsuperscript{2} scan of the Pt/Co multilayer.

**FIG. 2.** Measured phase-sensitive response of tunnel current to incident power modulation \( R \) for a \( p \)-type GaAs tip of 5×10\textsuperscript{17} cm\textsuperscript{3} doping density \( (x=\text{in-phase}, \, y=\text{out-of-phase}) \) vs incident laser power.

**FIG. 3.** (a) Circular dichroism image of magnetic bits written in a Pt/Co multilayer. Curves (b)–(d) represent topography, response, and circular dichroism, respectively, measured on a line scan over the two topmost bits, as indicated by the arrows in (a). Recorded with a \( p \)-type 4×10\textsuperscript{17} cm\textsuperscript{3} doped GaAs tip illuminated with 0.3 mW incident light power.
orders of magnitude. The response $R$ is essentially flat and merely shows a gradual lateral variation, probably due to differences in light power arriving at the tip. It is only in the CD signal that the bits become clearly visible.

The difference of CD within versus outside the bits yields a value for the measured magnetic circular dichroism of 1.1%. Shining a 1 mm diameter laser beam through the homogeneously magnetized part of the Pt/Co multilayer onto a macroscopic photodetector, we measured a MCD of 1.4%. This difference can be ascribed to multiple reflections taking place between the apex of the GaAs tip and the metallic sample; the presence of GaAs in close proximity to the place between the apex of the GaAs tip and the metallic This difference can be ascribed to multiple reflections taking place between the apex of the GaAs tip and the metallic sample; the presence of GaAs in close proximity to the place causes an enhanced optical transmission and a reduced MCD. When the tip was retracted from the sample by $0.5 \mu m$, i.e., at a distance larger than the tip radius, a measurement of the MCD using the displacement current gave the same value as measured with the photodetector. The observation that the CD is not precisely reversing sign when the tip is placed on one of the bits we attribute to the presence of a nonmagnetic contribution to the CD signal. This can be caused by the combination of an element shifting the optical phase and a polarizing element. A phase shift may be introduced by a tilt of the sample with respect to the light propagation direction, while polarization sensitivity can originate from a tip being tilted or having low symmetry at the apex.

In Pt/Co multilayers the domain wall width is of the order of the grain size, which is 10 to 20 nm in our case. From the steepest edges observed in our images we estimate the lateral optical resolution of a $p$-type GaAs tip of $10^{17} \ cm^{-3}$ doping density to be 250 nm at the specified operating conditions. This resolution is determined by the extent to which photocarriers generated in the tip are able to reach the apex and tunnel into the counter electrode. The collection volume of photocarriers will be determined by several physical parameters, such as the tip shape, the penetration depth of the light, the photocarrier diffusion length and the depletion field profile. In our experiment we illuminated the junction with 0.3 mW light power using a 20 $\mu m$ spot diameter. Taking account of 20% optical transmission through the sample, and using a photon-to-electron conversion efficiency of 100%, we find a maximum density of photocarrier current arriving at the semiconductor surface of 0.1 $\mu A/\mu m^2$. Since we were drawing 0.5 nA of tunnel current, we can estimate the minimum collection area of photogenerated charge to be approximately (70 nm)$^2$. This value is of the same order as the measured lateral optical resolution squared. The important point here is that although the tip is scanning in full illumination, causing both near-field as well as far-field radiation to be absorbed in the tip, the tip volume that can supply carriers to the tunneling current is limited due to the various electrical transport lengths involved. A further decrease of the collection volume could be achieved by properly chosen semiconductor materials or nanostructured composite tips. The resulting reduction of detectable photocarrier current has to be compensated for by increasing the optical power. Special care will have to be taken to avoid heating signals to start dominating, for example by increasing the modulation frequencies. As an example, having 10 mW light power absorbed in the tip, 20 $\mu m$ spot diameter, and drawing 0.5 nA of tunnel current, we estimate a lateral optical resolution of 6 nm to be achievable with a tip having an optimized collection volume of photocarriers.

Finally, it is interesting to note that our measurement technique allows for studies of both electrical and magnetic sample ordering by using circular and linear light polarizations. The technique may be operated in both a transmission and a reflection geometry. A measurement scheme that is closely related to the above presented technique is spin-polarized tunneling by optical orientation in GaAs. Magneto-optical interactions are sensitive to bulk magnetization, whereas spin-polarized tunneling is sensitive to the spin density of electronic states at the sample surface. The respective effects may be separated by their dependence on excitation wavelength, surface preparation, and bias voltage. Ideally, we envisage a combination of the two measurements, so as to be able to simultaneously measure sample topography, bulk magnetization, and surface spin density with (sub) nanometer resolution.

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