Electric Force Microscopy for the Characterization of Phase-Change Storage Materials

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Abstract

A theoretical model describing the image formation process in electric force microscopy is developed, and applications for imaging bit structure in phase-change and ferroelectric materials are described.

1. Introduction

Phase change optical recording media have become increasingly promising for high-density and high-data rate storage, and are finding particular application in current and future DVD applications. In the recording process it is important to be able to write small, regularly-shaped bits and to erase them efficiently. Various microscopic methods are used to image recorded bit structure to help understand the record and erase processes, thereby optimizing material parameters, disk structure and recording strategy. In particular, TEM and AFM techniques are often used to visualize bit structure. More recently, various types of electric field microscopy have been shown to produce excellent contrast between amorphous and crystalline regions in phase-change materials[1,2] .

Electric force (or field) microscopy is often used as a general term for several types of scanning electrical microscopy. Scanning Kelvin Probe Microscopy (SKPM) (also known as Scanning Maxwell stress Micrsocopy - SMM) essentially measures contact potential (and can be very effective for imaging phase-change media -see refs 1 & 2 for example). Scanning Capacitance Microscopy, as the name implies, measures tip-sample capacitance and, with heterodyning, can be very useful for investigating the high-frequency operation of integrated circuits. Electric or Electrostatic Force Microscopy (EFM) responds to the gradient of the electrostatic force exerted between the tip and the sample, and it is this form of imaging that is the main interest of this paper. We develop a theoretical framework to describe the physical interaction between tip and sample in EFM, applying it to the case of imaging of phase-change and ferroelectric media. It is intuitively obvious that the size and form of the tip is expected to be a crucial factor limiting the detection and observation of images. However in previously published theoretical studies of EFM (in all its forms), the tip characteristics do not appear explicitly in the imaging process. In an alternative, reciprocal, approach to understanding force microscopy, originally applied to magnetic force microscopy (MFM) systems[3,4] , the role of the tip is quite obvious. We have therefore extended the reciprocity approach to the case of electric force microscopy and developed a computer simulation to predict the performance of EFM systems and the images to be expected from them.

2. Theory

In MFM, a magnetized tip is scanned over and close to the surface of a magnetic sample, and magnetic forces act on the tip causing it to deflect. By monitoring this deflection, an image of the 'magnetic structure' of the sample can be produced. Conventionally the magnetic force acting on the tip can be expressed as

$$F_z^{tip} = -\int_{tip} \sum_i M_i^{tip}(r') \frac{\partial H_i^{samp}(r+r')}{\partial z} d^3 r' \qquad (1)$$

where i represents x, y or z coordinates, $M_i^{tip}(r')$ is the x, y or z component of magnetization of an elemental volume of the tip and $H_i^{samp}(r{+}r')$ is the stray field from the sample at the position of that elemental tip volume. In the 'reciprocity-based' approach the forces between sample and tip are interchanged by applying the third law of Newton, and the role of tip field in the imaging process is explicitly revealed[3,4] . Eqn (1) can thus be rewritten as

$$F_z^{samp} = -F_z^{tip} = \int_{samp} \sum_i M_i^{samp}(r') \frac{\partial H_i^{tip}(r+r')}{\partial z} d^3 r' \tag{2}$$

where $M_i^{samp}(r')$ is the magnetization of an elemental volume of the sample and $H_i^{tip}(r{+}r')$ is the stray field from the tip at that volume element.

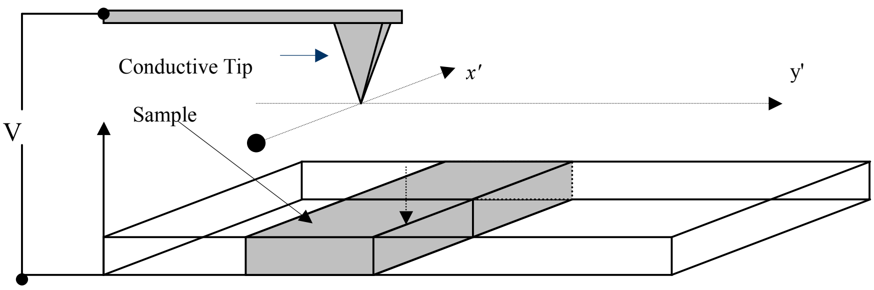


Fig. 1 General tip-sample arrangement for electric force microscopy

In the EFM case, shown in Fig. 1, an electric potential is applied between the tip and sample and, as the tip is scanned in close proximity to sample, electric forces act on the tip and cause it to deflect, so producing an image. By analogy with MFM, we can apply a reciprocity approach to the EFM case in which the electric field produced by the electrically charged tip interacts with the electric polarization of the sample to produce an electric force. In certain types of sample, such as ferroelectrics, the electric polarization may be inherent to the material and unaffected by the presence of the tip (i.e. equivalent to the permanent magnetization of a 'hard' ferromagnet); in such cases the force generated in the EFM is a direct analogy of the MFM description of eqn (2) and can be written

$$F_z^{samp} = \int_{samp} \sum_i P_i^{samp}(r') \frac{\partial E_i^{tip}(r+r')}{\partial z} d^3 r' \tag{3}$$

where $P_i^{samp}(r')$ represents polarization of the an elemental volume of the sample, $E_i^{tip}(r{+}r')$ is the stray electric field from the tip at that elemental volume and other constant factors have been omitted.

In materials without a permanent electric polarization, such as dielectrics, the electric field from the tip may induce a non-permanent polarization. In this situation the polarization induced is related to the applied tip field by the equation

$$\mathbf{P} = \varepsilon_o(\varepsilon_r - 1)\,\mathbf{E}_{tip} \tag{4}$$

where ε_r is the relative permittivity . Thus, we can rewrite the electrostatic force in this case as

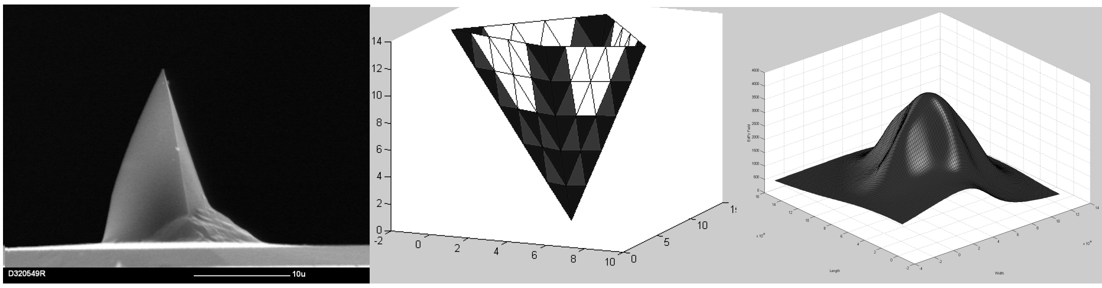
$$F_z^{samp} = \int_{samp} \sum_i \varepsilon_o(\varepsilon_r - 1) \frac{\partial \left(E_i^{tip}(r+r')\right)^2}{\partial z} d^3 r' \tag{5}$$

where again the role of the tip field in the imaging process is explicitly revealed (indeed the tip here has two roles, inducing polarization and then imaging this induced polarization).

3. Results and Discussion

A computer simulation of the EFM imaging process has been developed, based around eqns (3) and (5). The simulation runs under the Matlab™ environment on a standard IBM-type PC.

The first step in the process is to calculate the electric field emanating from the tip. This is achieved by assuming a particular electric charge distribution on the tip surfaces. To speed the calculations, charges are distributed on rectangular or triangular sheets on the tip surface, and the total field calculated from the sum of the fields from these sheets. Triangular sheets of charge are well-suited to typical tip geometries, and have been used previously in the study of MFM imaging[5]. In Fig. 2, for example, we show the field produced by a typically-shaped pyramidal tip.



(a) (b) (c)

Fig. 2. (a) SEM image of typical AFM tip, (b) distribution of triangular charge sheets on tip surface, (c) electric field distribution below tip with charge distribution of (b)

Once the electric field from the tip is known, the image from a particular sample can be calculated. In the case of materials with an 'inherent' or 'permanent' polarization, such as ferroelectrics, the image is calculated by implementing eqn (3) and the situation is directly analogous to that of MFM imaging of ferromagnetic samples. As an example we show in Fig. 3 the predicted image due to rectangular bits or domains in a ferroelectric-type material with a normalized polarization of ±1. For simplicity the tip in this case was represented by a flat rectangular charge sheet placed parallel to the sample surface and separated from it by 60 nm.

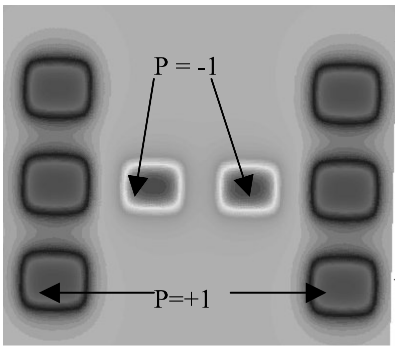
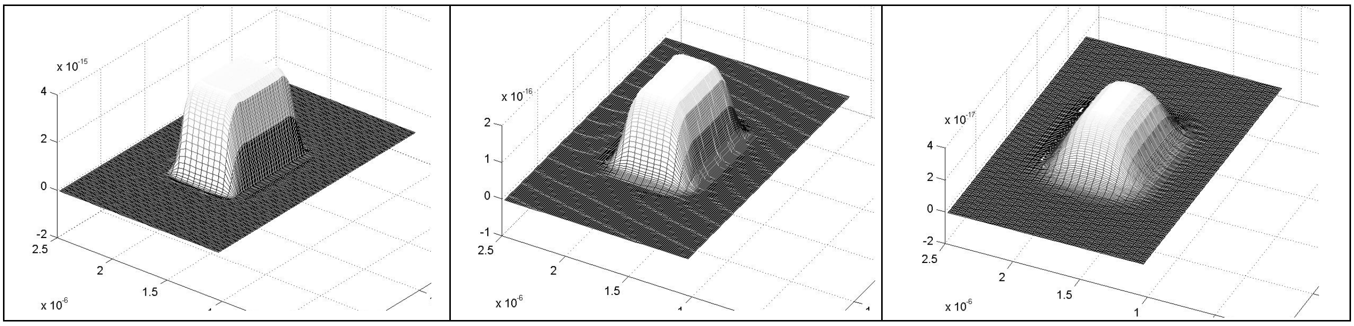


Fig. 3. EFM image of 300x500 nm rectangular bits or domains in a ferroelectric material with a normalized polarization ±1 and for a tip-sample distance is 60 nm.

For materials that do not posses an inherent polarization, such as dielectrics, the tip field itself may induce a non-permanent polarization, as already explained in §2 above, which in turn leads to the generation of an interaction force between the tip and sample. It is this effect that may be responsible for the image contrast observed when imaging phase-change media in the electric force microscope, since we expect amorphous and crystalline regions to exhibit significantly different permittivity values. In Fig. 4, for example, we show the simulated image arising from a small rectangular bit in a phase-change material, calculated according to eqn (5). In this case the image is dependent on the gradient of the square of the electric field from the tip, and it is reasonable to expect that different tip geometries will generate quite different images - an expectation that we are currently investigating both theoretically and experimentally. We are also examining the possibility of describing the Scanning Kelvin Probe Microscopy technique from a reciprocity approach, so that the role of the tip in this commonly used imaging process can also be determined.



(a) (b) (c)

Fig. 4. Simulated EFM images of a 300x500nm 'bit' written into a phase-change medium for tip-sample separations of (a) 20nm, (b) 60nm and (c) 120nm. Scanned area is 1.5x0.9µm.

References

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