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Non-linear polaronic conduction in magnetite nanowires

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ABSTRACT

We report the temperature dependent current (I) – voltage (V) characteristics of Fe_3O_4 nanowires with varying width (w) of 132, 358, and 709 nm. While the widest nanowire (w=709 nm) shows ohmic I (V) curves for all temperatures, those for w=132 and 358 nm show nonlinearity, which can be expressed by a combination of linear (V) and cubic (V^3) terms. The behaviour of conductance (linear bias component of current) and non-linearity in these nanowires is related to small polaron hopping related conduction. Moreover, we observed an anomalously large hopping lengths, which may be related to the size of percolation cluster and/or antiphase domain. Our study presents first experimental evidence for such non-linear polaronic conduction in magnetite nanowires.

1. Introduction

Nanostructured materials provide enormous opportunities to explore intriguing physics, which can lead to various remarkable properties from their counterparts due to confinement effects [1]. In particular, the magnetic nanostructures have been studied extensively in recent years [2–14]. When the geometric dimension approaches the magnetic length scales such as domain wall width or exchange length, the electrical conduction in these nanostructures is determined by the effects like domain wall motion and spin polarised electron tunnelling [4,5]. From the application point of view, these can be utilised in various spintronics devices due to high storage density, non-volatility, low power consumption, and high speed in comparison to the conventional electronic devices. Therefore, a great deal of effort has been devoted in creating nanostructures of various half metallic ferromagnets [2–14]. Among these materials, Fe_3O_4 with high Curie temperature (T_C) of 860 K and ~100% spin polarisation is a promising candidate for creating such structures, which can be utilised in spintronics devices operating at room temperature. Fe_3O_4 has been already employed to create one-dimensional structures like nanocontact [4], nanoconstriction [5], and nanowire [7–14]. These structures show various extraordinary features like large (8000%) magnetoresistance, spin filter effects, excellent microwave absorbability etc. Moreover, these studies report non-ohmic conduction even at low biases, which has been attributed to domain wall motion, Coulomb blockade, Schottky barrier formation, and tunnelling across antiphase boundaries [4,5,8,12]. Apart from these effects, the non-linear charge conduction can arise due to a more fundamental phenomenon like the hopping of small polarons present in magnetite. In this report, we have investigated the current (I) – voltage (V) characteristics of magnetite nanowires as a function of width (132, 358, and 709 nm) and temperature (200–300 K). Our study presents the evidence for such non-linear polaronic conduction in magnetite nanowires for the first time.

2. Experimental details

While Fe_3O_4 nanowires have been grown using hydrothermal conversion route, vapour–solid growth, and electrospinning route [7–11], we have created the nanowires from pulsed laser deposited epitaxial magnetite (Fe_3O_4) film using focused ion beam (FIB), which is considered as one of the most accurate and precise way of creating nanostructures. The thin film (thickness t=50 nm) of Fe_3O_4 on (100) oriented MgO single crystal substrate was deposited using KrF excimer based pulsed laser deposition technique. The deposition was performed in high vacuum (~10^{-5} m bar) at a temperature of 450 °C. An energy density of 0.8 J cm^{-2} was used to ablate α-Fe_2O_3 target placed at a distance of 5 cm from the substrate. We have checked the film morphology using atomic force microscopy (AFM). The AFM image shown in Fig. 1(a) reveals smooth and homogeneous growth of the film with

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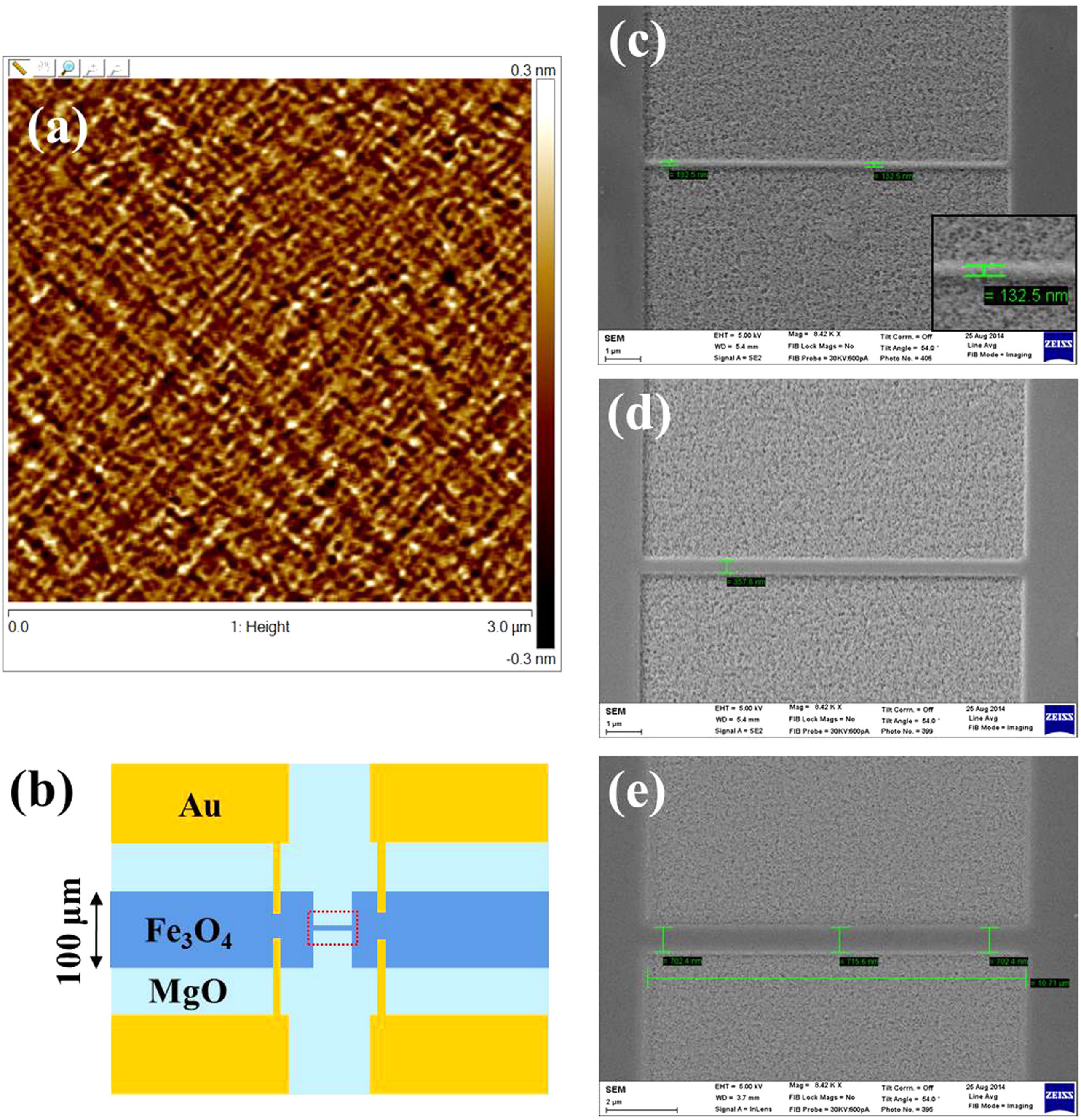

Fig. 1. (a) The 3 × 3 μm² AFM image of the film. (b) Schematic diagram of nanowire geometry. (c–e) The SEM images of three different nanowires.

root mean square roughness value of 0.2 nm. To fabricate nanowires, we have created a 100 μm wide line from Fe_3O_4 film using photolithography and Ar^+ ion milling [See Fig. 1(b)]. Four 100 nm thick Au pads were thermally evaporated on the top to take out electrical contacts. Then, three $l=10$ μm long nanowires of different widths (w) were patterned using FIB. The scanning electron microscope (SEM) images display sharp and well defined nanowires of three different widths [See Fig. 1(c–e)]. While the structural characterisation for the film was performed by X-ray diffraction (XRD), the transport measurements in four-probe geometry were performed in superconducting quantum interference device with a transport probe and cryogenic probe station.

3. Results and discussion

The $\theta-2\theta$ XRD pattern for Fe_3O_4 film grown on (100) MgO substrate is displayed in Fig. 2(a). The epitaxial growth of Fe_3O_4 film can be verified by the presence of only (h00) peaks. The $\theta-2\theta$ XRD scan close to (400) peak reveals the presence of film peak at $2\theta=43.14°$ in addition to the finite-thickness oscillations [See the inset of Fig. 2(a)], which indicates the high quality growth of the films. The bulk lattice constant (8.396 Å) of Fe_3O_4 is slightly smaller than twice of lattice constant of MgO (4.212 Å). This small lattice mismatch leads to tensile strain in the film. Thus, the in-plane lattice constant of Fe_3O_4 film should increase while out-of-plane lattice constant ($a_\perp$) should decrease. We have calculated