CHIN.PHYS.LETT. Vol. 25, No. 11 (2008) 4113

Electrical and Magnetic Properties of $FeSi_2$ Nanowires

PENG Zu-Lin(彭祖林)[1**], S. Liang[2]

[1]*School of Science, Beijing Institute of Technology, Beijing 100081*

[2]*Science and Engineering of Materials Program, Arizona State University, Tempe, AZ, 85287, USA*

(Received 17 July 2008)

We report the characterization of self-assembled epitaxially grown $FeSi_2$ nanowires (NWs) in terms of electrical and magnetic properties. NWs grown by reactive deposition epitaxy (RDE) on silicon (110) show dimensions of 10 nm×5 nm, and several micrometres in length. By using conductive-AFM (c-AFM), electron transport properties of one single NW is measured, resistivity of a single crystalline $FeSi_2$ NW is estimated to be 225 μΩ·cm. Using superconducting quantum interference device (SQUID), we measure a magnetic moment of 0.3 ± 0.1 Bohr magneton per iron atom for these $FeSi_2$ NWs.

PACS: 73. 63. Nm, 75. 75. +a

Transition-metal silicides (Fe, Co, Ni) are widely used as contacts and interconnects in current microelectronics[1] and potential optoelectronic devices.[2] One-dimensional nanowires are promising building blocks for bottom-top microelectronics scheme, due to their novel properties, such as electrical, mechanical and magnetic properties. Self-assembled, epitaxial silicide NWs were first reported by Preinesberger *et al.*[3] These NWs possess the following properties: excellent crystal quality, generally single crystal; easy fabrication, self-assembly; different properties readily available (metallic, magnetic and semiconducting). Since silicide NWs are epitaxially self-assembled on silicon surface, this allows patterning according to different crystal orientation, surface steps etc. Other advantages of silicide NWs include: direct compatibility with ULSI processing, and stable interface/junctions with silicon. The Schottky barriers formed between metallic silicide NWs with Si offer a natural electrical isolation. These Schottky diodes can be employed to fabricate field-effect transistors[4,5] and NW heterostructures, i.e. metal-Si-metal structure.[6]

Iron silicides are very interesting because they have different phases (properties): α (metallic), β (semiconducting), γ and s-phases (magnetic and metastable). The semiconducting phase with band gap of 0.87 eV[7,8] is favourable for optical fibre communication systems operating at 1.5 micron wavelength. Among all transition metal silicides, $FeSi_2$ is the only reported light emitter.[9,10] The NW shape is thought to result from an anisotropic lattice mismatch that is small ($< 1\%$) in the long direction and large ($> 5\%$) in the short direction. For any potential applications of NWs, it is prerequisite to know their various properties. In this Letter, we report electrical and magnetic properties of self-assembled epitaxially grown $FeSi_2$ NWs.

Experimental procedures are Si(1 1 0) samples (miscut angle $< 0.5°$, phosphorous-doped, about 10 Ωcm) were cleaned in ultrahigh vacuum by degassing for 12 h, followed by flashing multiple times at 1250°C for several seconds, using resistive heating. Iron was deposited by sublimation from a 4N-purity iron wire onto the heated silicon substrate, this is the so-called reactive deposition epitaxy (RDE). Coverage was determined in situ using a crystal thickness monitor, with an accuracy of 20%. Coverage values are given in monolayer (ML) units, where 1 ML $= 4.78 \times 10^{14}$ iron atoms/cm^2. Temperature was determined using an optical pyrometer (emissivity 0.4), with an accuracy of ±20°C. AFM images were obtained using a Digital Instruments NanoScope Ⅲ in tapping mode. Electrical properties of NWs were measured by using PicoScan 2500 from Molecular Imaging. C-AFM was used to measure NW resistance. One electrode is the conductive AFM tip, and the other electrode is a macro-pad of gold to partially cover NWs. The gold macro-pad was deposited through a sharp mask by physical vapour deposition. MPMS XL5-AC SQUID magnetometer, superconducting quantum interference device (SQUID), were used for magnetic moment of these $FeSi_2$ NWs.

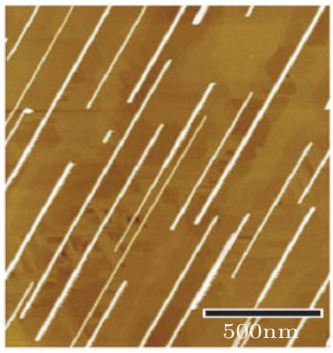


Fig. 1. AFM image of iron silicide NWs, Z height range is 10 nm, taken by tapping mode.

**Email: pclin@bit.edu.cn

© 2008 Chinese Physical Society and IOP Publishing Ltd

Figure 1 shows AFM image of iron silicide NWs, Z height range is 10 nm, taken by tapping mode. NWs are well-aligned along the Si ⟨110⟩ direction, therefore perfectly parallel to each other. NW cross section and length depend on various growth conditions, such as growth temperature and dose rate. Here for these samples, we grew NWs at 700°C with 1-2ML iron deposition. This AFM image clearly shows that sizes of NWs are about 10 nm×5 nm and several micrometres in length. Figure 2 shows the largest aspect ratio occurs at about 700°C, which is why we choose this temperate for NW growth. At low temperature around 600°C, silicide nucleation happens everywhere, and NWs aspect ratio is small; for high growth temperature around 800°C, Ostwald ripen causes aspect ratio small too.

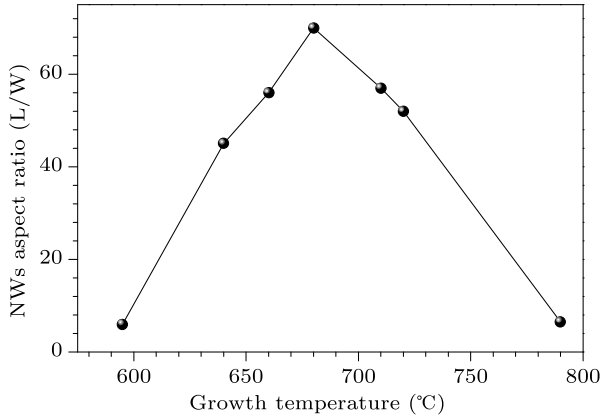


Fig. 2. Aspect ratio of NWs vs growth temperature.

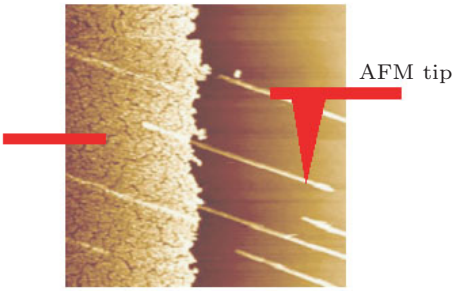


Fig. 3. Schematic of c-AFM measurement of NW resistance.

Self-assembled silicide NWs can be metallic, semiconducting or magnetic. Unlike carbon nanotubes and other NWs, which have reached a mature level of study, silicide NWs are relatively new and offer unique opportunities for nanoelectronics. Since silicide NWs are epitaxially self-assembled on silicon surface, this allows patterning according to different crystal orientations, surface steps etc. Resistivity of these single crystalline NWs is intrinsic properties, which need to be characterized for any further potential applications. Figure 3 presents the schematic diagram of c-AFM measurement of NW resistance. Macro gold pad was deposited by PVD through a sharp edge. This macro gold pad partially cover NWs, and conductive-AFM tip acts as another electrode, which can also move to change the NWs measurement length.

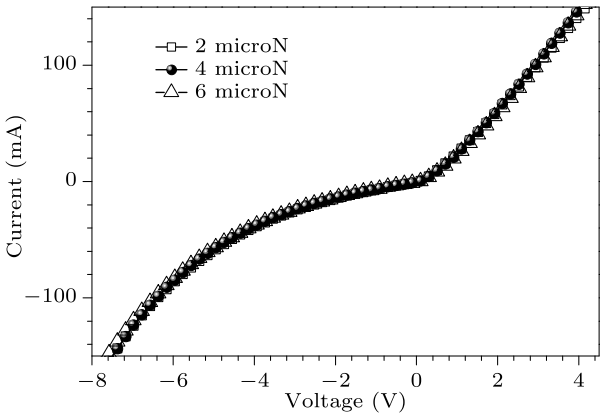


Fig. 4. Resistance measurement $I-V$ curves of one single NW.

Figure 4 shows the resistance measurement $I-V$ curves of one single NW. For c-AFM, the conductive tips are the most critical part in the measurement, in terms of reliability, accuracy and durability. In this work, we use solid tungsten tip for electrical characterization. Both gold pad and metallic NW form Schottky diodes with the silicon substrate. Thus one diode is always reverse biased when voltage ramps from negative to positive. There is current with a linear behaviour from −2 V to 0.5 V. This current is thought to be dominantly through the NW. Based on the resistance and from repeated measurements we obtain 29.7 kΩ for NW with length of 400 ± 50 nm and NW cross-section area estimation of 30 nm^2. $FeSi_2$ NW resistivity would be less than 225 μΩ·cm. NW's intrinsic resistance should be lower than 29.7 kΩ since this number still includes contact resistance. Single-crystal metallic nickel silicide (NiSi) NWs, with diameter 15–45 nm, were reported to have ideal resistivity of about 10 μΩ·cm and remarkably high failure current densities, $> 10^8 A{\cdot}cm^{-2}$. Self-assembled single crystalline cobalt silicide NWs, with diameter of about 60nm, were measured *in situ* by multi-tip scanning tunnelling microscope and had a resistivity of 30 μΩ·cm.[11] However, there are also reports on much higher resistivity of NWs compared to bulk, such as $NiSi_2$ NWs, with resistivity about 800 μΩ·cm.[12] Carbon-coated nickel silicide NWs, average diameter ranging in 20–40 nm, have resistivity about 370 μΩ·cm at room temperature.[13] For bulk silicides, rare earth silicides have resistivity ranging in 100–300 μΩ·cm,[14] Transitional metal silicide resistivity is about 20–50 μΩ·cm, but $CrSi_2$, VSi_2 and $MnSi_2$ approach 1000 μΩ·cm.[15] $FeSi_2$ thin film (iron deposited thickness is 4–100 nm) annealed from 400–950°C for 10–40 s, has a resistivity of about 60–

80 μΩ·cm at room temperature.[16] Using c-AFM, we obtain $\rho = 225\,\mu\Omega\cdot$cm for NWs. One can expect that the resistivity in the NWs to be larger than bulk values due to intrinsic effects including interface scattering along the length of the NW and possibly one-dimensional confinement effects. Both would be larger for small NW cross-section.

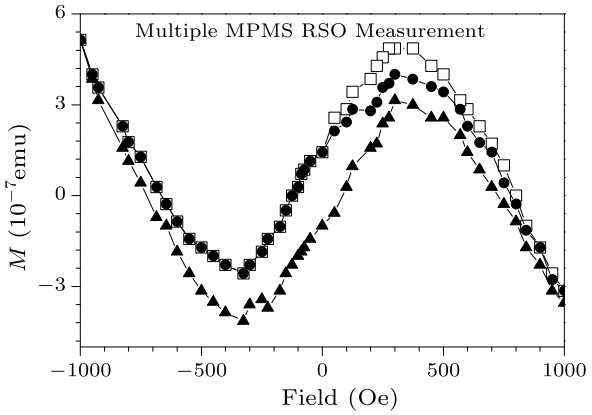


Fig. 5. Magnetic response of the nanowires, measured at 2 K with silicon substrate. The applied magnetic field H is parallel to NWs.

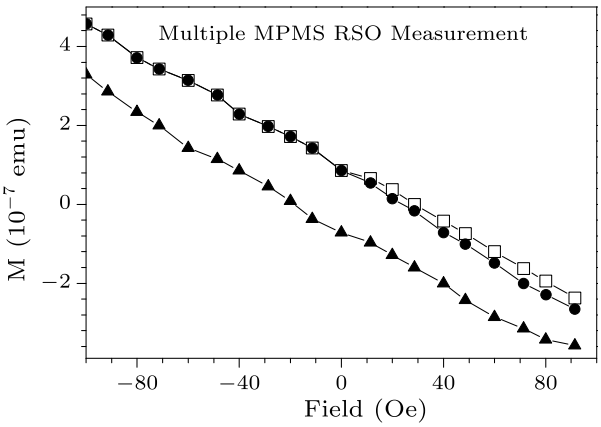


Fig. 6. Magnetic response of the silicon substrate, measured at 2 K.

Figure 5 shows magnetic response of the nanowires, measured at 2 K with a silicon substrate, the applied magnetic field H is parallel to NWs. Figure 6 shows magnetic response only from the silicon substrate, measured at 2 K, which clearly shows diamagnetic behaviour. Figure 7 shows the magnetic response of NWs without silicon substrate. This 2 K $M(H)$ hysteresis is clearly a ferromagnetic signature with a saturation magnetization of about 1.6×10^{-6} emu and a coercive field of 30 Oe. Based on the average coverage of 1–2 ML and the sample area of 0.5 cm^2, this corresponds to a magnetic moment of 0.3 ± 0.1 Bohr magneton per iron atom. Compared to other wires, our silicide NWs have many advantages over other wires, such as single crystalline, perfectly ordered, easily control of NWs size and density, etc. This opens their applications in high-density storage and nanosensors. These NW arrays are promising candidate materials for ultrahigh density perpendicular magnetic recording media, with the potential for terabits per square inch density, due to the predictable enhanced perpendicular magnetic performance after appropriate annealing.[17] The wires may consist of a single element or a magnetic alloy. Currently, the fabrication of NWs based on porous alumina membranes is very popular due to the easily controllable pore sizes and chemical and mechanical properties,[18,19] other methods include lithography (either optic or electron-beam lithography) or template-synthesis by utilizing diblock copolymer,[20] track-etched membranes.[21] Novel methods have been introduced recently even though they are not mature and have very low efficiency right now. For example, SPM lithography using either AFM or STM, step decoration, nanoimprint, focused ion beam milling etc. However, the high cost and serial processing format of these techniques may limit their utility. The dimensions of nanowires in the current literature are in the range of 20–200 nm. Theoretical work on magnetic NWs is not extensively reported.[17] The (Fe, Co, Ni)–Pt alloys are important magnetic materials due to their large uniaxial magnetocrystalline anisotropy ($K_{\mathrm{u,FePt}} = 6.6\times10^6$ Jm^{-3}, $K_{\mathrm{u,CoPt}} = 4.9\times10^6$ Jm^{-3}), satisfactory mechanical strength, and good chemical stability.[22] Recently, researchers reported the fabrication of Fe–Pt, and Co–Pt nanowires with diameters of 50–100 nm from porous alumina films and found preferential magnetic characteristics in the perpendicular direction.[23] Fabricating magnetic nanowire arrays with ultrahigh density is particularly intriguing to achieve enhanced performances for ultrahigh density perpendicular magnetic recording media.

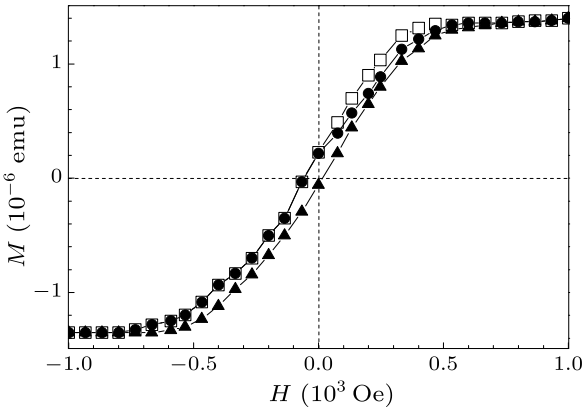


Fig. 7. Magnetic response of NWs without silicon substrate, measured at 2 K. The applied magnetic field H is parallel to NWs.

In summary, we have presented and characterized self-assembled epitaxially grown $FeSi_2$ silicide nanowires (NWs). NWs grown by reactive deposi-

tion epitaxy (RDE) on silicon (110) show dimensions of 10 nm×5 nm, and several micrometres in length. Conductive-AFM (c-AFM) is a simple way to measure a single NW resistance. Resistivity of a single crystalline $FeSi_2$ NW is estimated to be 225μΩ·cm. Using a superconducting quantum interference device (SQUID), we measure a magnetic moment of 0.3 ± 0.1 Bohr magneton per iron atom for these $FeSi_2$ NWs. This opens their application in high-density storage and nanosensors.

References

[1] Kittl J A and Hong Q Z 1998 *Thin Solid Films* **320** 110
[2] Reeson K J, Sharpe J, Harry M, Leong D, McKinty C, Kewell A, Lourenco M, Chen Y L, Shao G and Homewood K P 2000 *Microelectron. Eng.* **50** 223
[3] Preinesberger C, Vandre S, Kalka T and Daehne-Prietsch M J 1998 *Phys. D: Appl. Phys.* **31** L43
[4] Saitoh W, Yamagami S, Itoh A and Asada M 1999 *Jpn. J. Appl. Phys.* Ⅱ **38** L629
[5] Snyder J P, Helms C R and Nishi Y 2002 *Appl. Phys. Lett.* **67** 1420
[6] Wu Y, Xiang J, Yang C, Lu W and Lieber C M 2004 *Nature* **430** 61
[7] Wan Q, Wang T H and Lin C L 2003 *Appl. Phys. Lett.* **82** 3224
[8] Bost M C and Mahan J E 1985 *J. Appl. Phys.* **58** 2696
[9] Birdwell A G, Glosser R, Leong D N and Homewood K P 2001 *J. Appl. Phys.* **89** 965
[10] Leong D, Harry M, Reeson K J and Homewood K P 1997 *Nature* **387** 686
[11] Okino H, Matsuda I, Hobara R, Hosomura Y, Hasegawa S and Bennett P A 2005 *Appl. Phys. Lett.* **86** 233108
[12] Comrie C M, Falepin A, Richard O, Bender H and Vantomme A 2004 *J. Appl. Phys.* **95** 2365
[13] Lee K S, Mo Y H, Nahm K S, Shim H W, Suh E K, Kim J R and Kim J J 2004 *Chem. Phys. Lett.* **384** 215
[14] Thompson R D and Tu K N 1982 *Thin Solid Films* **93** 265
[15] Smirnov A, Tove P A, Pires J S and Norde H 1980 *Appl. Phys. Lett.* **36** 313
[16] Tokarev V V, Kibardin A V, Pyatkova T M and Zarovsky D I 1990 *Appl. Surf. Sci.* **44** 235
[17] Chu S Z, Inoue S, Wada K and Kurashima K 2005 *Electrochim. Acta* **51** 820
[28] Sander M S, Gronsky R, Sands T and Stacy A M 2002 *Adv. Mater.* **14** 665
[19] Furneaux R C, Rigby W R and Davidson A P 1989 *Nature* **337** 147
[20] Thurn-Albrecht T, Schotter J, Kastle G A, Emley N, Shibauchi T, Krusin-Elbaum L, Guarini K, Black C T, Tuominen M T and Russell T P 2000 *Science* **290** 2126
[21] Kelly D, Wegrowe J E, Truong T K, Hoffer X and Ansermet J P 2003 *Phys. Rev.* B **68** 134425
[22] Sellmyer D J 2002 *Nature* **420** 374
[23] Huang Y H, Okumura H, Hadjipanayis G C and Weller D 2002 *J. Appl. Phys.* **91** 6869