Plasmonic Tuning of Effective Phase Transition Temperature and Electrical Conductivity

James Frame[1], Wakana Kubo[2,3] and Xu Fang[1]*
[1]Department of Electronics and Computer Science, University of Southampton, Southampton SO17 1BJ, United Kingdom
[2]Department of Electrical and Electronic Engineering, Tokyo University of Agriculture and Technology, 2-24-16 Naka-cho, Koganei-shi, Tokyo 184-8588, Japan
[3]Metamaterials Laboratory, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
** Author e-mail address: x.fang@soton.ac.uk*

Abstract: Thermo-plasmonic engineering at the nanoscale can control material properties at the macroscopic scale. We demonstrate utilising plasmonic resonance to tune the effective phase transition temperature and electrical conductivity of vanadium oxide thin films.
OCIS codes: (160.3918) Metamaterials; (250.5403) Plasmonics; (130.3060) Infrared

1. Introduction

Plasmonic resonance induces strong light absorption at the nanoscale. It is a property that has been explored for many applications. For example, we recently demonstrated using coherent absorption in ultrathin metamaterials for optical data processing [1,2] and selective excitation [3-5]. Here we utilise thermal energy generation that accompanies light absorption for controlling material properties at the macroscopic scale. This work may lead to new kinds of tuneable optical and optoelectronic metamaterials and metadevices.

We demonstrate the plasmonic influence on the optical and electrical properties of vanadium oxide (VO_x). The interplay between surface plasmons and phase change materials including vanadium dioxide, chalcogenides, and indium tin oxide has been intensively studied. Indeed, it is widely viewed as a promising strategy to construct reconfigurable metamaterials and meta-devices. VO_x was chosen for this study for three main reasons: its optical and electrical properties change drastically across the metal-insulator phase transition; the phase transition temperature is close to room temperature (68 °C for VO_2 and lower for other stoichiometry); VO_x is the key material in infrared focal-plane arrays that currently dominate the market of uncooled infrared sensors.

2. Results and discussion

We have investigated several different sample configurations, with gold and silver nanorods buried inside or grown on top of VO_x thin films. As an example, Figure 1a shows an array of gold/chromium nanorods on top of a silicon substrate. The thicknesses of the gold layer and the adhesive chromium layer are 40 nm and 5 nm, respectively. The nanorods were subsequently covered with a layer of VO_x which was ~70 nm in thickness.

Figure 1b shows the simulated electric field distribution of a 2D plane located 10 nm above the nanorod top surface within the VO_x layer. The field distribution shows strong electric field confinement at the two ends of the nanorods, a clear feature of localised surface plasmon resonance. In contrast, such field enhancement and localisation are absent if the polarisation of the incident light is along the short axis of the nanorod (Figure 1c).

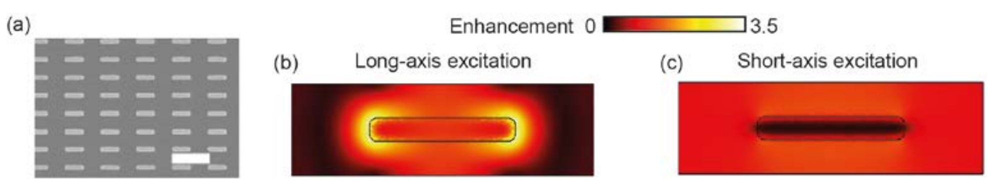

Figure 1. Nanorod morphology and plasmonic resonance. *(1) Several samples were fabricated following a conventional electron beam lithography process. This panel shows a part of a sample after the lift-off step which contains gold/chromium nanorods on top of a silicon substrate. The nanorods were subsequently coated with a thin layer of vanadium oxide. The scale bar is 1 µm. (2) Electric field distribution of a 2D plane located 10 nm above the nanorod top surface within the VO_x layer. Field strength is normalised against the value at the same location inside a plain VO_x film. The wavelength is the plasmonic resonance wavelength of 3.8 µm. The temperature is 25 ºC. The incident light is polarised along the long axis of the nanorod. (3) Corresponding field distribution for light polarised along the short axis of the nanorod. The field localisation and enhancement observed in (2) are absent here.*

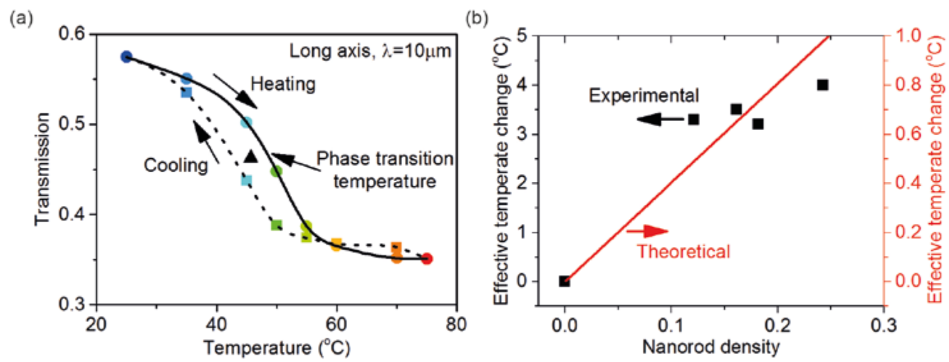

Figure 2. Plasmon induced suppression in effective phase transition temperature. *(1) Transmission hysteresis loop at 10 µm, a wavelength far away from the plasmonic resonance, obtained in a complete heating (solid line) and cooling (dashed line) process. The effective phase transmission temperature (black triangle) is at the centre of the loop. (2) Change in the phase transition temperature measured in five samples (black dots) and calculated using computational simulation and theoretical analysis (red line).*

Figure 2a shows the transmission hysteresis loop of the sample measured at 10 µm, a wavelength far away from the plasmonic resonance. This is a unique aspect of this work, as it allows for the isolation and analysis of intrinsic material properties. The incident light is polarised along the long axis of the nanorod and excites localised surface plasmons. The effective phase transition temperature is defined as the centre of the loop, corresponding to 45.7 ºC. This value is 3.3 ºC below the value measured under the orthogonal light polarisation (i.e. without plasmonic resonance). This result is interpreted through combining the effective medium principle and extending the analysis in Reference 6 (Figure 2b). We further measured the surface electrical conductivity on similar samples to determine the extent of plasmonic influence on electrical properties.

3. Conclusion

To conclude, we have demonstrated control over the effective phase transition temperature and electrical conductivity of vanadium oxide via the thermo-plasmonic effect. Metal nanorods embedded in and grown on top of vanadium oxide thin films support surface plasmon resonances, in turn generating thermal energy that is highly localised and inhomogeneous. This inhomogeneity at the nanoscale leads to suppression of the phase transition temperature and electrical resistivity measured at the macroscopic scale. This phenomenon depends on nanorod density and polarisation of the incident light, making it both controllable and reversible. This work shows a new way of controlling macroscopic material properties through thermal nano-engineering.

Acknowledgements

This work was supported by the tenure-track programme of the Tokyo University of Agriculture and Technology (TUAT), the JST-PRESTO programme of the Japan Science and Technology Agency (JST), the Royal Society (Research Grant RG170314), and the Daiwa Anglo-Japanese Foundation (Daiwa Foundation Award 5453/12324).

References

[1] X. Fang, M. L. Tseng, J. Y. Ou, K. F. MacDonald, D. P. Tsai & N. I. Zheludev, "Ultrafast all-optical switching via coherent modulation of metamaterial absorption," Applied Physics Letters 104, 141102 (2014).
[2] X. Fang, K. F. MacDonald & N. I. Zheludev, "Controlling light with light using coherent metadevices: all-optical transistor, summator and invertor," Light: Science & Applications 4, e292 (2015).
[3] X. Fang, M. L. Tseng, D. P. Tsai & N. I. Zheludev, "Coherent excitation-selective spectroscopy of multipole resonances," Physical Review Applied 5, 014010 (2016).
[4] X. Fang, K. F. MacDonald, E. Plum & N. I. Zheludev, "Coherent control of light-matter interactions in polarization standing waves," Scientific Reports 6, 31141 (2016).
[5] M. L. Tseng, X. Fang, V. Savinov, P. C. Wu, J. Y. Ou, D. P. Tsai & N. I. Zheludev, "Coherent selection of invisible high-order electromagnetic excitations," Scientific Reports 7, 44488 (2017).
[6] G. Baffou, P. Berto, E. B. Ureña, R. Quidant, S. Monneret, J. Polleux & H. Rigneault, "Photoinduced heating of nanoparticle arrays," ACS Nano 7, 6478 (2013).