Nanophotonics research at QUB

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The main nanophotonics research activities at the Queen's University of Belfast are focused on nano-optics and near-field optical microscopy, linear and non-linear spectroscopy and materials characterisation at the nanoscale, surface plasmons and surface plasmon polaritons, nano-plasmonics, electromagnetic field enhancement and light confinement on the nanoscale, linear and nonlinear optical properties of nanostructured metal, ferromagnetic and ferroelectric thin films, photonic and polaritonic band-gap structures, active (all-optical) photonic devises as well as quantum optics.

1. INTRODUCTION

The QUB team has expertise in nano-optics and near-field optical microscopy, linear and non-linear spectroscopy and materials characterisation on the nanoscale, scanning probe microscopy, optical and functional properties of nanostructured metal, ferromagnetic and ferroelectric thin films and nanostructures and quantum information processing theory. In this paper the range of facilities available to the team and some of the recent research programmes are described.

2. FACILITIES

Fabrication and characterisation facilities at QUB cover material synthesis and nanofabrication, structural and functional characterisation, linear and nonlinear optical measurements, and scanning probe microscopy.

Fabrication facilities include FEI FIB2000 focused-ion-beam microscope and machining system; multi-target UHV sputter deposition of metallic and magnetic thin films, multi-layers and superlattices with in-situ monitoring; pulsed laser deposition of dielectric, ferroelectric and piezoelectric ceramic thin films, multi-layers and superlattices; bulk ceramic and metallurgical processing.

Structural characterisation facilities comprise of FEI Tecnai F20 high resolution transmission electron microscope, JEOL 6400 SEM, Bruker-AXS D8 XRD, Digital Instruments STM/AFM/MFM, piezo-AFM.

State-of-the-art scanning near-field microscopes, surface wave spectroscopy, non-linear spectroscopy, magnetic materials testing including magneto-optical analysis, ferroelectric/piezoelectric testing forme a comprehensive suite for optical, electrical and magnetic characterisation of nanomaterials and devices.

3. NONLINEAR NANO-OPTICS FOR MATERIAL CHARACTERISATION

The trends in the miniaturisation of electronic devices and components and continuous improvement in their areal density require non-destructive material characterisation at smaller and smaller scales. The performance of new materials such as thin ferroelectric films, layered magnetic structures, spin-valves and tunnelling junctions is determined by their properties at microscopic level, particularly by the sizes of magnetic (or electric) domains and domain boundaries. Therefore it is important to develop high-resolution techniques for characterisation of the micromagnetic and magneto-optical properties, which would enable for a bottom-up approach in search of new functional materials with the specific properties. The scanning near-field optical microscope (SNOM) opens the opportunity to probe the local optical field distribution over surfaces and thus visualise the functional materials with sub-wavelength optical resolution. Near-field microscopy of second harmonic generation (SHG), which combines very high surface sensitivity of SHG with high spatial resolution provided by SNOM, has significant potential for probing the nonlinear optical response of a surface locally (Fig. 1). The data obtained in such measurements may allow for comparison of experiment and theory in sufficient detail to study the essential features of the functional material behaviour and the underlying microscopic electrodynamics and material science.[1–4]

4. LINEAR AND NONLINER SURFACE POLARITONIC CRYSTALS

In its simplest form a surface plasmon polariton (SPP) is an electromagnetic excitation that propagates in a wave like fashion along the planar interface between a metal and a dielectric medium, and whose amplitude decays

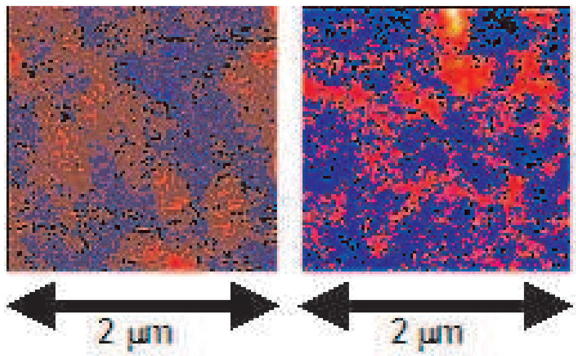

FIG. 1: Topography (left) and the polarisation-dependent SHG variations from the PZT thin film.

exponentially with increasing distance into each medium from the interface.[5,6] The intrinsically two-dimensional nature of SPPs provides significant flexibility in engineering SPP-based all-optical integrated circuits needed for optical communications and optical computing. The relative ease of manipulating SPPs on a surface opens an opportunity for their application to photonics and optoelectronics for scaling down optical and electronic devices to nanometric dimensions. Most importantly, active photonic elements based on nonlinear surface plasmon polariton optics, which allow controlling optical properties with light, are much easier to realize with suitably patterned metal surfaces, due to the SPP-related electromagnetic field enhancement near a metal surface.[5,6]

A periodic arrangement of defects on a metaldielectric interface should exhibit the properties of a one or two-dimensional polaritonic crystal when the periodicity of the surface structure is comparable with the wavelength of the SPPs propagating on the interface. A complicated system of band gaps has indeed been calculated and measured using different metallic gratings and bi-gratings.[5,6] A complete analogy can be achieved in this case with 2D photonic crystals.

We have used focused ion beam (FIB) milling of various metal films (Au, Ag, Co, Ni) to fabricate surface-polaritonic crystals consisting of arrays of periodic holes of various shapes and sizes. This technique can be used for thin (a few nm) as well as thick (a few hundred nm) metal films on a substrate. The control over the size and shape of individual elements allows us to control SPP Bloch modes on nanostructured metal films and thus conventional (3D) optical properties of nanostructured metal films.[7,8]

Nonlinear surface polaritonic crystals allow to achieve a strong photon-material coupling needed for the realisation of various architectures ranging from a very low light intensity switching in photonics to a single photon detector with high efficiency.[9] This requires development of new types of (meta)material systems where this coupling can be enhanced and provide the enhancement of light coupling to material excitations using intermediate states of various surface plasmon modes, such as surface plasmon polaritons, localised surface plasmons and cylindrical surface plasmons.

One of the realisations of nonlinear SPP crystal is the combination of nanostructured metal film with nonlinear materials that reduces the light intensities needed for achieving nonlinear effects. For example, the nonlinearity was observed on the 200 nm hole array structures at the two control light wavelengths (488 and 514 nm) related to the Kerr-type third-order nonlinearity. This has allowed to observe both nonlinear transmission and bistability in transmission of surface polaritonic crystals.

5. SELF-ORGANISED TEMPLATES FOR FERROMAGNETIC AND METALLIC NANOSTRUCTURES

The anodisation of aluminium is a promising technique in self-assembly research, and nano-porous alumina templates have already been used to fabricate a range of nano-particles and wires. Recent work by other groups has shown that it is possible to produce self-assembled anodised aluminium nanostructures on planar substrates allowing compatibility with thin film processing techniques. Usually, the process involves the deposition of a relatively thick aluminium film (3–10 μ m) followed by a double anodisation procedure to leave typically 1-2 μ m long pores with hole widths of 25–250 nm and hole spacings from 50–300 nm. A new procedure utilising a single anodisation step of aluminium thin films followed by normal incidence ion milling (the procedure is currently filed for patenting) has recently been developed at QUB. The templates produced can then either be deposited on in situ by a physical vapour method or they can be removed from the vacuum chamber, and the holes filled or capped by a chemical deposition method. The unique shape of the templates after normal incidence ion milling means that despite conformal coverage by physical vapour deposition, it is still possible to produce nanometre arrays of various materials using a second low angle ion milling stage. The actual hole dimensions and spacing are controlled by the acid type and voltage used. Fig. 2 illustrates the successful creation of Co nano-dots following the conformal sputtering of a Co thin film, and then the low angle ion beam milling mentioned above. Fig. 3 demonstrates the creation of lead zirconium titanate (PZT) nano-dots at the top of the nano-pores, produced in a single step dip into an aqueous PZT solution, followed by annealing.

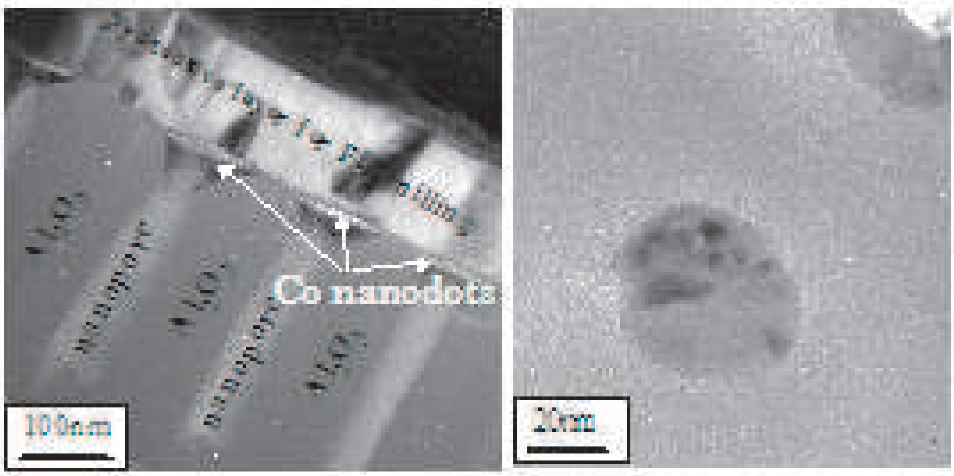

FIG. 2: (Left) Co nanodots formed at surface of the alumina. (Right) Plan view of a Co nanodot formed on template.

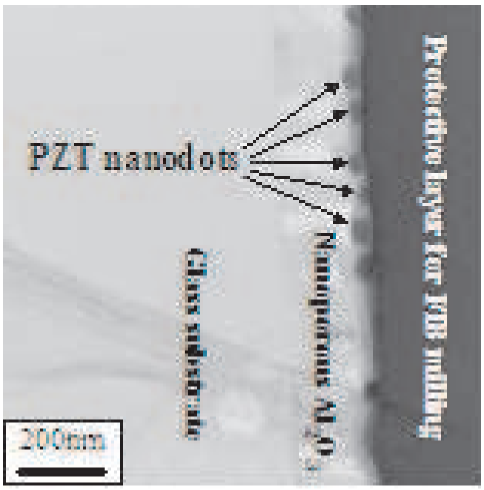

FIG. 3: PZT nanodots formed on the alumina template

Electrochemical deposition in alumina templates followed by the chemical removal of the matrix allows to achieve arrays of free standing metallic nanowires acting as optical antennas (Fig. 4).

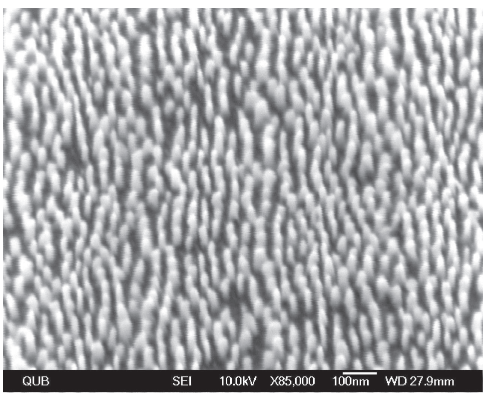

FIG. 4: The Au nanowire array achieved after removing the alumina template.

6. MAGNETO-PLASMONIC STRUCTURES

Magneto-optical properties of nanostructured thin metal films is another important area of research at QUB.[10] We study the influence of nanostructuring on magnetic properties and domain structure in thin films as well as magneto-optical properties of the structures capable of supporting surface plasmon polaritons. In a concurrent approach, magneto-optical studies of Co nanodots and nanowires deposited in the self-organised templates described above are also under investigation both *ex situ* and *in situ*.

7. QUANTUM OPTICS AND INFORMATION PROCESSING

Theoretical work is carried out on studies of quantum nature of light-molecule interactions for possible use in quantum gate operation.[11] Several other issues of quantum information processing are under investigation related to single photon detection and its influence on operation of quantum communication systems[12] and the effects of nonlinearities for optical realisation of quantum information processing, such as a photon-subtracted state to increase nonclassicality of a light field which comes from nonlinear interaction.[13]

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