Nanostructured optical metamaterials

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Effective light-trapping within solar cells requires reflection, refraction or diffraction to couple incident light into a waveguiding mode of the absorbing layer. Commonly used schemes are based on the micron-scale patterning of a back reflector or the surface of a cell or both. Reciprocity is a key issue: to ensure multiple reflections some form of asymmetry is required and this is can be difficult to realise cheaply. Often random or diffuse reflectors are used as a low cost but imperfect solution. Our objective is to realise effective light-trapping by exploiting new optical metamaterials.

An example of this type of technology, is our work on planar chiral metamaterials where arrays of metallic and dielectric planar chiral nanostructures have been fabricated and shown to have pronounced effects on the polarization state of diffracted light. Here we will briefly review the significant differences in polarization properties that are observed for metallic and polymer structures, most notably differences in the induced ellipticity for transmitted light [1,2].

In solar cells, we believe that the lithography of similar sub-wavelength features in regions above or below active layers will allow us to exploit optical non-locality and create optical metamaterials capable of coupling light for appropriate ranges of polarisations, angles of incidence and wavelengths by using pseudo-random (quasicrystalline), or scaled fractal patterns etched into thin layers on either side of the active layer.

Our proposed techniques should have a number of important advantages, in addition to providing longer effective absorption lengths, deep etches should no longer be necessary, while we can envisage that in an industrial production line nanostructured layers could be cheaply provided by the rapidly developing nano-imprinting technologies.

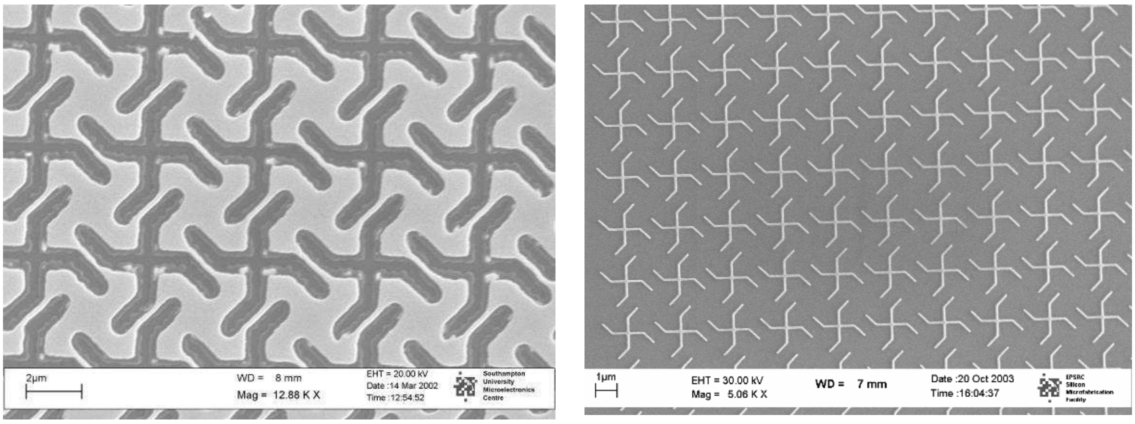

Fig. 1 (a) SEM images of planar chiral optical metamaterials (1,2)

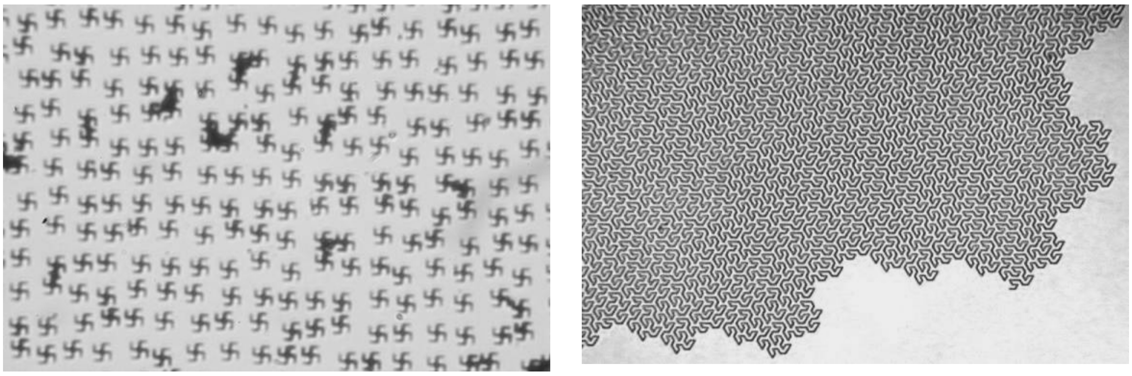

Fig. 1 (b) Optical images of planar random and fractal chiral optical metamaterials (unpublished)
(both pictures are on similar scale, the gammadions are ~ 1µm across)

The high cost of silicon as a solar cell material has stimulated the development of cells only a few micrometers thick and these will require light trapping schemes that employ surface texturing on the sub-micron scale. At these length scales, diffractive effects could be exploited to achieve large changes in the direction of light propagation, forcing the light to travel through the cell at oblique angles and so greatly increasing the effective optical thickness of the cell [3]. By engineering the shape of diffraction gratings on the scale of a period (blazing), the diffraction envelope maximum can be tuned to an order higher than the zeroth. A typical saw-tooth or échellette grating (figure 2) achieves this but shading problems mean that the efficiency of the grating is degraded when designed for large angle diffraction [4]. We would like to tackle this issue by using sub-wavelength features to create blazed gratings for efficient large angle diffraction (figure 3) [4-7]. Our aim is to fabricate thin film solar cells and employ blazed diffraction gratings with sub-wavelength features as a light trapping scheme (figure 4).

Patterning on the sub-wavelength scale can also be used to produce antireflective coatings that reduce reflection from a surface over broader wavelength ranges and larger angles of incidence than traditional single or multilayer antireflection coatings. Reflections occur at an interface between two materials because of a sudden change in refractive index. By texturing on the sub-wavelength scale at the interface, a more gradual change in refractive index can be introduced and so such reflections can be significantly reduced (figure 5). We aim to use this technique as an alternative to multilayer antireflection coatings to reduce unwanted reflections and so maximise the proportion of incoming light that is coupled into our solar cells.

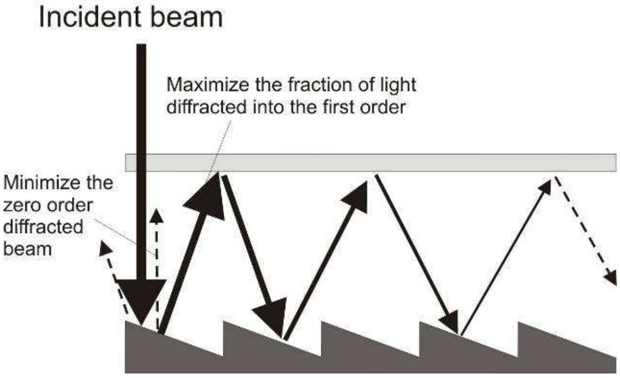

Fig. 2 Light trapping with a blazed diffraction grating (from [3])

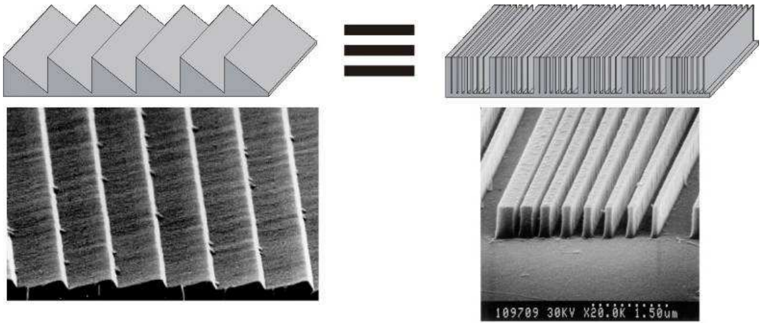

Fig. 3 Sub-wavelength texturing can be used to form blazed gratings that diffract light efficiently by large angles (SEM images from [3] and [6])

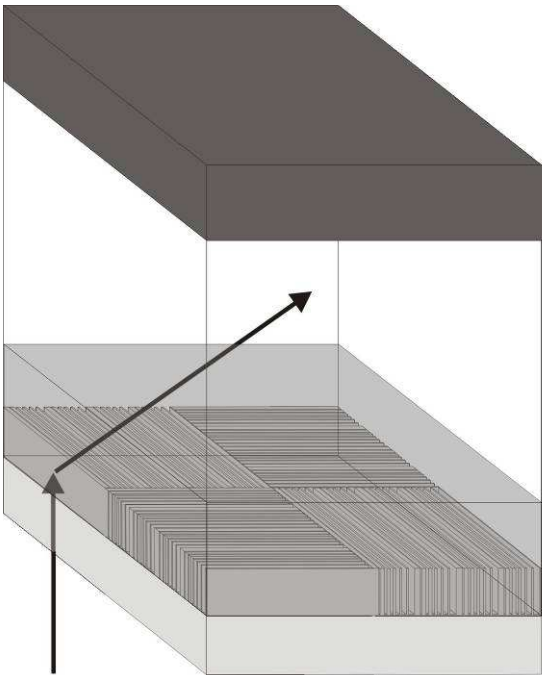

Fig. 4 Light trapping in a solar cell using blazed sub-wavelength gratings.

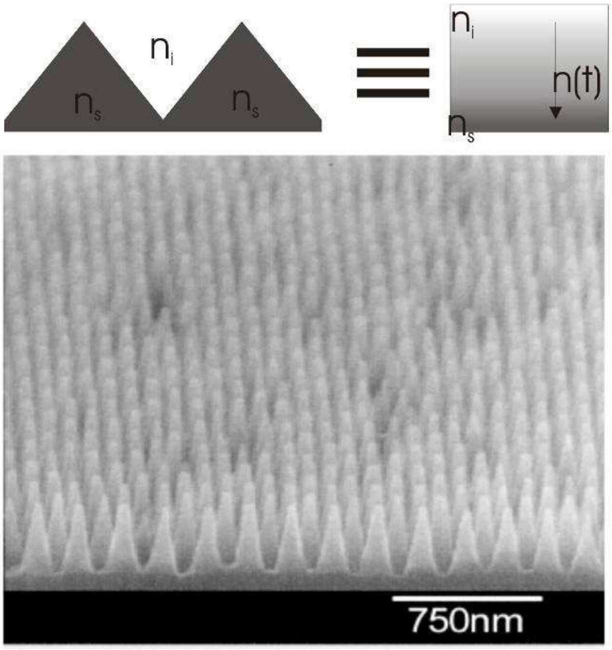

Fig. 5 Sub-wavelength texturing to reduce reflection. (SEM image from [7]

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