Nanoscale aluminum dimples for light-trapping in organic thin-films

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Figure 1. SEM images of AAO fabricated in phosphoric electrolyte: top view (a) and cross section (b). Corresponding Al-dimple pattern transfer after removal of the AAO (top view (c) and side view (d)).

Figure 2. Top view SEM images of Al dimple structures fabricated from (a) Sulfuric, (b) Oxalic, and (c) Phosphoric. Top view SEM images of Al dimples covered with PMMA after laser ablation in (a) Sulfuric, (b) Oxalic, and (c) Phosphoric.

Figure 3. Cross-sectional transmission electron microscopy showing the thin Al layer (bar) and the periodic structure of the dimples (arrow). Scale bar: 200nm.

Figure 4. Top view SEM images of Al dimples fabricated in phosphoric electrolyte with different concentrations: (a) 40%, (b) 60%, (c) 80%, and (d) 90%.

Figure 5. Top view SEM images of Al dimples fabricated in phosphoric electrolyte with different concentrations: (a) 40%, (b) 60%, (c) 80%, and (d) 90%.

Figure 6. Top view SEM images of Al dimples fabricated in phosphoric electrolyte with different concentrations: (a) 40%, (b) 60%, (c) 80%, and (d) 90%.

Figure 7. Reflectivity measurements of Al dimples with P3HT/PCBM blend on top and fabricated from phosphoric electrolyte.

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Motivation

Integration of nanostructures in organic solar cells (OSCs) has been investigated extensively in the past few years as an alternative way for enhancing the power conversion efficiency of the devices. Incorporating structured electrodes in the solar cell architecture holds potential for light absorption improvement in the active layer of the devices. A prospective, cheap and large-scale compatible method for structuring the electrodes in OSCs arises by the use of anodic aluminum oxide (AAO) membranes.

In the present work, aluminum films of high purity and low roughness are formed via e-beam evaporation of a few nanometers of aluminum followed by a micrometer layer of aluminum formed via sputter deposition. The samples are then anodized to form nano-scale pores of controlled sizes. The anodization of the prepared samples occurs in an electrochemical cell in H₂SO₄, H₂CO₃ and H₃PO₄ solutions. The fabricated AAO is selectively etched in H₂CO₃/H₃PO₄ mixtures, in order to reveal the underlying aluminum nanoscale dimples, which are present at the bottom of the pores.

The dimples are covered with a thin layer of PMMA and the impact from different dimple dimensions is investigated experimentally via laser ablation field mapping (experimentally), which is compared to FDTD calculations to further explain the mechanisms of light-trapping in these structures.

AFM characterization of Al dimples

AFM characterization of various Al dimple samples has shown that the Al dimples consist of peaks that can reach up to 350nm in height (phosphoric). Different electrolyte acids lead to different dimple morphology, where the anodization of the Al is the guiding force for the dimple structural formation.

SEM characterization of Al dimples and ablation samples on Si substrate

The anodization of Al in different electrolytes results in various dimple dimensions, average dimple diameters are 30nm for sulfuric (a), 90nm in oxalic (b) and 280nm in phosphoric (c). Dimple samples are covered with 200nm of PMMA and scanned with a 790nm femtosecond pulsed laser beam. Due to dimensional limitations of the dimples and thickness of the PMMA, local field enhancement from the edges of the dimples is more evident for dimples made from phosphoric electrolyte (f), rather than those made from sulfuric (d) and oxalic (e) electrolytes.

Fabrication

The pore diameter of the AAO pattern, top view (a) and cross section (b), depends strongly on the anodization parameters (sample temperature, voltage, electrolyte). The formation of pores transfers a dimple like pattern to the Al below the AAO (red circulated area in (b)). Selective etching of the AAO in H₂CO₃/H₃PO₄ mixtures reveal the underlying nanoscale Al dimples, top view (c) and tilted cross section (d).

Numerical Simulations (FDTD)

Broadband, three dimensional (3-D) Finite-difference time-domain (FDTD) simulations support the experimental outcome. We employed a hexagonal, periodic lattice of spherically shaped Al dimples with a PMMA top layer. Perfectly matched layers (PML) sandwich the unit cell in z-direction, whereas Bloch periodic boundaries surround the unit cell in the layer plane. A plane wave source with normal incidence, polarized perpendicularly to the dimple ridges, excites the structure. A Fourier transformation leads to the (wavelength-dependent) electromagnetic field power distribution within the unit cell.

Outlook

It has been shown that Al dimples easily can be fabricated from AAO templates, and that such nanostructures exhibit light trapping effects. The dimples can potentially serve as nanostructured electrodes in P3HT/PCBM bulk heterojunction organic solar cells, and the fabrication of such OSC devices is currently under investigation. Preliminary results indicate that the organic blend covers homogeneously the Al dimples structures (Figure 6) while the Al dipoles show improved absorbance compared to planar Al electrodes (Figure 7). The origin of this effect is from combined field-enhancement at the edges of the dimples along with diffuse scattering from the dimples.