Nanofabrication by ultra-high resolution environmental scanning electron microscopy

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Gas mediated electron beam induced processing is a maskless technique capable of material deposition and removal at sub-10 nm length scales. However, fabrication of functional nanostructures is limited by beam spread in bulk substrates, substrate charging, and delocalized processing occurring around the nominal structures. Here, we overcome these problems by performing etching and deposition using ultra-high resolution magnetic immersion lens environmental scanning electron microscopy (ESEM)[1] instead of the conventional precursor delivery method that entails gas injection into a high vacuum specimen chamber through a capillary located near the substrate. Benefits of the ESEM approach include the ability to use high gas pressures (>1 kPa)[2] and efficient suppression of charging artifacts.[1,3] The latter is demonstrated by the use of bulk SiO_2 as substrate material for electron beam induced processing (Figs. 1 & 2).

Nanofabrication was performed using $C_6H_5CH{=}CH_2$, WF_6 and $Pt(PF_3)_4$ deposition precursors, and H_2O and XeF_2 etch precursors. Optimal process resolution is achieved using a two-step process. First, a deposition precursor is used to fabricate structures such as nanowires and nanopillars. Then, the deposits are slimmed by ESEM *imaging* in the presence of a second gas which acts as an etch precursor for the deposited material, but which does not etch the substrate (Figs. 1 & 2). During etching, the ESEM imaging signal provides direct visual feedback of the slimming process (Fig. 2), the rate of which can be controlled using the beam current density and pressure of the etch precursor. The minimum achievable feature size is limited by ESEM image resolution (~1 nm, under optimized conditions),[3] and by surface roughening occurring during etching.[1] Further control over process resolution and structure morphology is provided by parameters that affect the extent of precursor adsorbate depletion under the electron beam. These parameters include beam current density and precursor pressure, as is illustrated by Fig. 3. Benefits of the ESEM approach include the wide pressure range,[2] and the fact that the pressure at the substrate surface is equal to the directly measurable specimen chamber background pressure.

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[1] M. Toth, C. J. Lobo, W. R. Knowles, M. R. Phillips, M. T. Postek and A. E. Vladar, *Nano Letters* **7**, 525 (2007).
[2] M. Toth, M. Uncovsky, W. R. Knowles and F. S. Baker, *Appl. Phys. Lett.* **91** (2007).
[3] M. Toth, W. R. Knowles and B. L. Thiel, *Appl. Phys. Lett.* **88**, 023105 (2006).

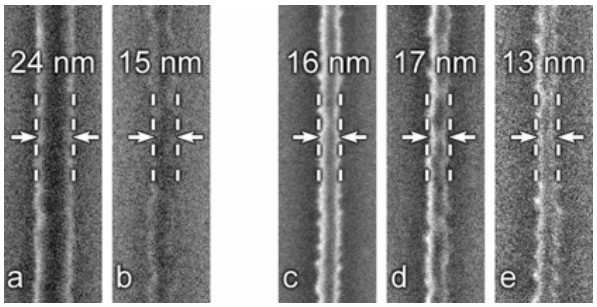

Fig 1: Carbonaceous nanowires fabricated on a bulk SiO_2 substrate. *(a, b):* two frames of a H_2O etch process used to slim the wire in (a). *(c-e):* similar nanowires slimmed to yield diameters in the range of 13 to 17 nm. [Deposition precursor: $C_6H_5CH=CH_2$, etch precursor: H_2O.]

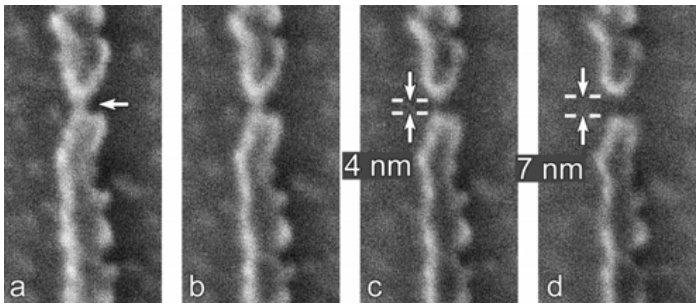

Fig 2: Four consecutive frames of a H_2O etch process used to slim a carbonaceous nanowire, and to produce the gap shown in (c-d). Gap growth was initiated by a stationary electron beam etch process (~ 1 s) in the region indicated in (a). [Deposition precursor: $C_6H_5CH=CH_2$, etch precursor: H_2O.]

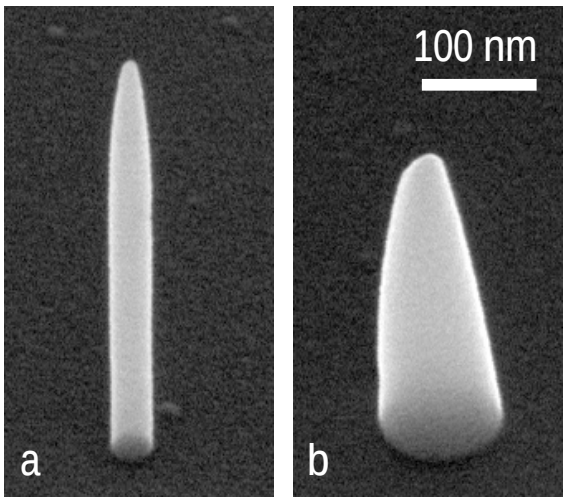

Fig 3: Pillars grown on Si using a stationary electron beam. The pillar aspect ratios were controlled by the beam current and precursor pressure – *(a):* 39 pA and 133 mTorr; *(b):* 1.13 nA and 275 mTorr. [Deposition precursor: WF_6]