Mass–transport and reaction-rate limited growth modes during electron–beam induced deposition

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Electron–beam induced processing (EBIP) is a direct–write technique well suited for the deposition and/or etching of nanoscale features [1]. Sub–10 nm spatial resolution [2] has been achieved; resolution limiting factors revealed [3,4] and the statistics of ~1nm resolution features quantified [5]. The success of EBIP as a nanofabrication process can be traced to several key advantages. The EBIP spatial resolution limit intersects the length scale where many nanoscale phenomena are realized < 20 nm. Moreover, nanoscale and 3D features can be grown at room temperature thus minimizing integration issues. EBIP is fully compatible with ancillary pattern generating soft/hardware used for electron beam lithography on conventional scanning electron microscopes making the process scalable.

Here we report pulsed EBID growth parameters that maximize the vertical growth efficiency (nm height per e^-) and minimize the lateral resolution of high–aspect ratio nanopillar features. Accelerating voltage, current, dwell time and precursor refresh times were varied to achieve the optimized condition. Results are discussed based on the interplay between emitted electron current density from the nanopillar and precursor gas coverage on and around the nanopillar during EBID. The precursor gas surface coverage is both space and time dependent near the growth spot during EBID due to the complex interaction between precursor vapor flux, surface diffusion, evolving nanopillar morphology, and the time–dependent electron flux impinging/emerging from the growing nanopillar. Nanopillars were grown under various mass–transport and reaction–rate limited (RRL) conditions by pulsed EBID. Under the RRL growth condition, the largest vertical nanopillar growth efficiency was obtained. Pulsed electron irradiation was a necessary step to achieve the RRL condition based on the precursor gas delivery system and the practical current limits. Varying the dwell and refresh time made it possible to vary the growth regime as well as tailor deposit morphology and vertical growth efficiency. Optimal lateral feature resolution as well as minimized collateral staining by scattered electrons is achieved in RRL EBID mode.

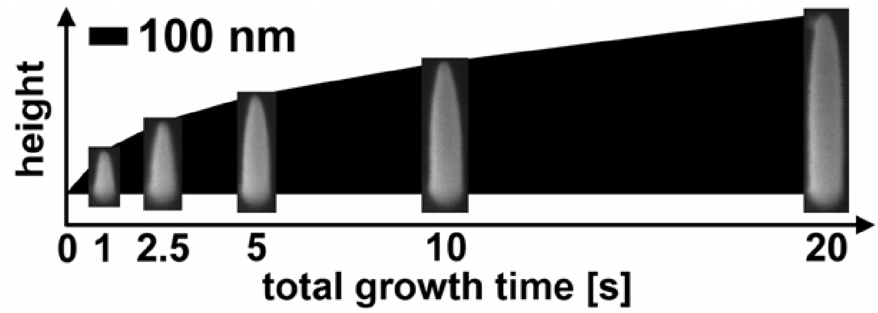

Figure 1 Mass–transport limited (MTL) EBID. Under MTL conditions, the rate of increase of nanopillar height decreases as a function of increasing total growth time (t_g). MTL is an inefficient mode of growth in terms of vertical growth efficiency and lateral nanopillar resolution. (30 keV, 79 pA, spot mode, localized gas injection for growth and no gas refresh time)

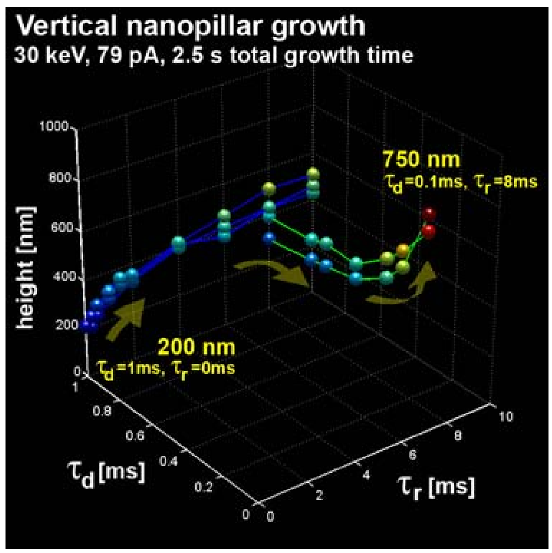

Figure 2 Vertical growth efficiency and lateral resolution can be increased by, introducing a refresh cycle (τ_r) coupled with a reduction in beam dwell time (τ_d), during each growth loop. Above, the increase in final nanopillar height is shown at a function of τ_r and τ_d at constant number of incident electrons. Thus, a taller nanopillar implies a greater EBID efficiency in terms of nm per electron. The efficiency increase is explained in terms of the interplay between the time and space dependent variables current density and precursor gas coverage.

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