Guided Assembly of Nanostructures via Electric Field Induced Surface Diffusion

I. Background and Scope: Fabricating ordered patterns of controlled shape, size and spacing at nanometer and micron scales has been an important goal of nano-scale science and engineering. Some of the applications envisaged for such processes include quantum dot devices, nano-composites and high density data storage devices. Most nanofabrication techniques are either top-down or bottom-up type. The top-down approach consists of examples such as photolithography, X-ray lithography, electro-deposition, scanning probe or electron beam lithography etc., which typically involve controlled micro- and nano-scale material removal to achieve patterned structures. On the other hand, in the bottom-up approach, one tries to exploit certain energetic or configurational forces acting at nano- and micro-scales to drive a self-assembly process. Typically, configurational forces arise as a result of a system's attempt to minimize its total free energy and the associated competition between the dominant contributions to the free energy. A well-known example is the strain induced island formation in epitaxial semiconductor thin films. However, there are difficulties in making use of self-assembly to fabricate devices of practical importance. For example, in the strain driven growth of semiconductor quantum dots, the resulting nanostructures usually do not possess the desired spatial order or uniformity. Thus, it is desirable to have a technique that can combine the driving configurational forces that underlie self-assembly processes and the spatial control that can be achieved in top-down processes. In this project, we demonstrate that spatial control can be achieved through a guiding electric field on the surface of electrically conductive materials. It is shown that, at sufficiently high temperatures, a gradient in electric field on the surface of a conductor can induce diffusion, leading to surface evolution.

II. Significant Results

We examined a number of model problems to quantify the driving force for diffusion due to an electric field and ascertain the necessary experimental conditions to realize electric field induced diffusion in practice. First, we examined the scenario shown in Fig. 1 where a uniform electric field of width w is applied normal to the surface of a conducting material. The system free energy consists of the surface energy and the electrostatic potential energy. Minimization of the free energy results in equilibrium perturbed shape of the surface, with an equilibrium island height proportional to the square of the applied electric field. For physically useful island height, it is determined that the electric field necessary is of the order of $10^8 - 10^9$ V/m, which can be achieved under high vacuum conditions.

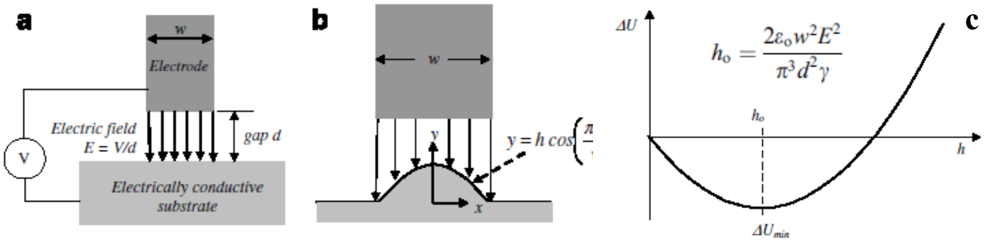

Figure 1. Perturbation of a conductive substrate subjected to a localized electric field. (a) An electrode close to a conductive surface sets up an electric field in the gap. The two solids constitute a capacitor. (b) Stability of the flat configuration can be examined by considering incremental changes in free energy due to small sinusoidal surface perturbations. (c) Schematic illustration of energy variation (ΔU) with perturbation amplitude h. Note that ΔU is minimum at ho given by the equation in the inset, corresponding to the equilibrium perturbation height.

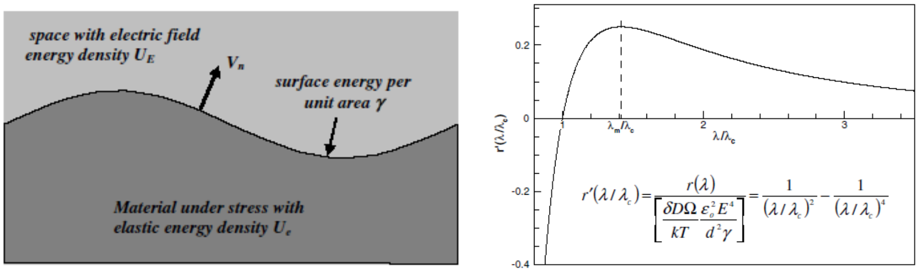

Figure 2. (top) Schematic illustration of a conductive solid with an evolving boundary in the presence of an electric field outside it. The surface normal velocity is V_n. (bottom) Non-dimensional perturbation growth rate as a function of its wavelength, showing the fastest growing mode.

Next, a linear perturbation analysis of a free surface subjected to a uniform electric field is carried out to examine its stability. A surface chemical potential is defined in terms of the local elastic energy density, surface energy and the local electrostatic energy density just outside the surface (Fig. 2a). The analysis predicts that perturbations above a critical wavelength are unstable, as shown in Fig. 2b. In order to realize the concept demonstrated by these analyses, an experimental set up was designed and built to subject the surface of a metal (gold was chosen as the model material) to an electric field. The temperature of the system is raised sufficiently high to accelerate surface diffusion. Figure 3 shows the experimental setup and some representative specimens the surfaces of which have undergone electric field induced surface diffusion and island growth. Very good agreement was found between the experiments and model predictions in terms of the time constants and length scales.

<u>These experiments, combined with the preceding analyses, demonstrate the basic phenomenon and serve as the starting point to develop a guided assembly technology through which any arbitrary micro-pattern geometry can be fabricated by appropriately modulating the electric field.</u>

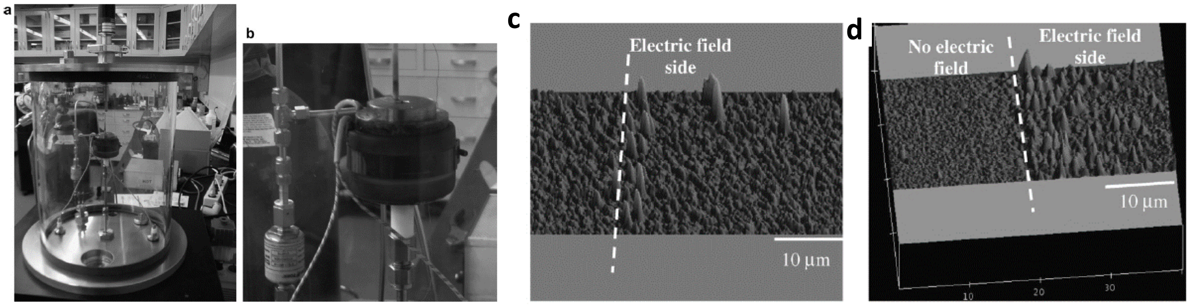

Figure 3. (a) A photograph of the process chamber constructed for the current experiments. (b) A close up view of the sample housing along with a heating element around it. (c) & (d) Representative experimental results. The dashed line is the approximate location of the edge of the top titanium electrode. The electric field was about 5 x 10^9 V/m in all cases. (c) T = 350° C, t = 7 h. (b) T = 240°C, t = 3 h.

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V. Publications:

1. V. Gill, P.R. Guduru and B.W. Sheldon. Electric Field Induced Surface Diffusion and Micro/Nano-scale Island Growth. *International Journal of Solids and Structures*. 45: 943-958. 2008.
2. V. Gill, Ph.D. Thesis, Brown University, 2009.