Nanofabrication with Lanthanum Hexaboride (LaB_6) for Nanoscale Vacuum Electronics

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Abstract: We present the first nano- and microfabrication of vacuum microelectronic components incorporating lanthanum hexaboride (LaB_6), a refractory low work function material with high electron emissivity. We design novel fabrication processes which yield ultra-low fill factor (<10%) nanoscale grids of 50 nm width on LaB_6 electrodes and nanoscale LaB_6 tips over ~mm^2 scales. We present a technique to fabricate these metal grids supported by nanoscale dielectric standoffs to precisely engineer electric fields applied to LaB_6 surfaces. Finally, we present applications of such nanostructures for a novel class of heat-to-electricity generator being developed at Modern Electron and ongoing R&D challenges with nanoscale vacuum electronic grids.

Keywords: lanthanum hexaboride, LaB_6, low-loss grid, low fill factor grid, microfabrication, nanofabrication, low work function, vacuum electronic, field emission heat engine.

Introduction

Maintenance of low work function surfaces is key to achieving high emission current densities from electron-emissive thermionic cathodes in vacuum electronic devices (VEDs) and to the efficiencies and power densities of thermionic-type heat-to-electricity converters. The low work functions afforded by Barium (Ba) and Cesium (Cs) have rendered these chemistries dominant in commercially available electron emitters; however, Ba and Cs chemistries suffer from two primary degradation mechanisms [1], which limit their lifetimes and applicability:

1. Ba and Cs are highly reactive with residual oxygen, water, carbon, and even other metals. Thus, pristine vacuum conditions are required to extend device lifetimes and prevent emitter poisoning, imposing significant vacuum hardware requirements.
2. Ba and Cs evaporate at relatively high rates at temperatures exceeding 900°C, so depletion of Ba/Cs reservoirs eventually yields an elevated work function of the cathode, and thus lower emission current. Similarly, miscalibration of cathode temperature can severely reduce the effectiveness of emitters [2].

These challenges are problematic for vacuum electronics which require high (>900°C) temperatures, harsh environments, and/or long-term use (e.g. space systems in which maintenance is practically impossible). Additionally, for low voltage applications (e.g. thermionic converters), the potential drop through the semiconducting Ba-based slurry on the surface of most commercially available cathodes is detrimental to device efficiencies, since electrons are emitted at lower energies, lowering collection efficiency and thereby exacerbating the negative impact of space charge buildup.

LaB_6 is an alternative low work function (2.6 eV) cathode material of fundamental and applied interest, since its use as a cathode material circumvents the aforementioned challenges with Ba. Specifically, LaB_6 is refractory (melting point ~2200°C), and thus its evaporation rate is relatively low even at temperatures as high as 2000°C. LaB_6 is also chemically inert, and thus is not easily poisoned by residual contaminants, despite its low work function. Finally, LaB_6 possesses practically metallic conductivity and a high Richardson's constant; thus thermionic LaB_6 emitters do not suffer from drastic voltage drops at their surface and have high electron emissivity.

Indeed, for the above reasons, several groups have characterized LaB_6 as an emissive material in high current density (~10s of A/cm^2) hollow [3] and knife-edge cathodes [4]. However, LaB_6 has not yet been incorporated into micro-scale VEDs yet, despite the consensus that microscale VED components can offer advantages such as lower required voltages, higher speeds, and low device footprints and masses compared to macroscale devices [5].

LaB_6 in nanofabricated vacuum electronics

Here, we present the first fabrication of nano- and microscale vacuum electronic components incorporating LaB_6. Specifically, we present a novel fabrication of ultra-low fill factor metal grids on LaB_6 electrodes and nanoscale pyramidal LaB_6 tips over mm^2-scale areas. These studies suggest that the chemically inert nature of LaB_6 enables its use as both an electrode and a substrate on which to fabricate nanoelectronic vacuum devices using standard cleanroom-based fabrication processes and tools.

Figure 1 presents a schematic fabrication process for nanoscale, low-fill-factor grids on LaB_6 electrodes. First, a LaB_6 film is deposited on an adhesive layer on a Si wafer via magnetron sputtering (we developed deposition conditions appropriate for our equipment using ref. [4] as a starting point). A dielectric is deposited on the LaB_6 and lithography is used to pattern metal lines. Finally, the dielectric is anisotropically etched using reactive ion etching which incorporates the metal lines as an etch mask. We note that the metal grid lines serve as both grids and etch masks in this fabrication process. In this case, we use Ti as adhesion layer, Si_3N_4 deposited by plasma-enhanced chemical vapor deposition as a dielectric support for the grid, and aluminum (Al) as the grid.

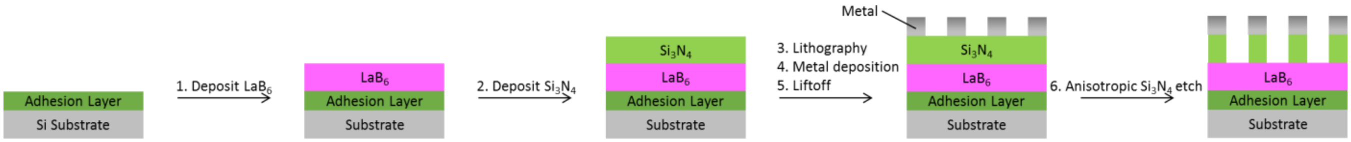

Figure 1. Nanofabrication process for high aspect ratio, low fill factor grids on LaB_6 electrodes.

Scanning electron microscope (SEM) images of gridded electrodes resulting from the above process are shown in Figure 2. The images reveal several key features. First, by adjusting parameters during the fabrication process, the aspect ratios and fill factors of the grid supports (and thus the electric field profile applied by the grid) can be readily tuned. For instance, Figures 2a and b show SEM images of grids fabricated using photolithography. The images reveal Al grid lines which are ~2.5 μm wide, spaced at 5 μm pitch, and offset from the LaB_6 electrode by ~1.5 μm thick Si_3N_4. Thus, these photolithography-defined grids have aspect ratios ~3:5 and fill factors ~50%. In contrast, nanolithography (in this case electron beam lithography) affords opportunities for ultrasmall, high-aspect-ratio low-fill-factor grids on LaB_6 electrodes. Figure 2c and d reveal resultant 50 nm-wide Al grid lines spaced at a pitch of 550 nm which subsequently served as etch masks for 500 nm tall Si_3N_4 supports, yielding record dielectric aspect ratios of 11:1 and low fill factors of ~9%.

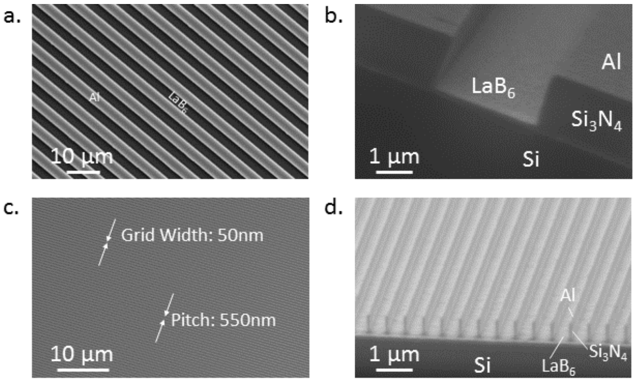

Figure 2. SEM images of micro- and nano-scale metal grids on LaB_6 electrodes. (a, c) Top down and (b, d) cross-sectional SEM images of grids on LaB_6 electrodes with line widths, pitches, fill factors, and dielectric support aspect ratios (a,b/c,d) of 2500/50 nm, 5000/550 nm, 50%/9%, and 3:5/11:1, respectively.

Second, electron microscope inspection of the LaB_6 before and after the fabrication process shows that the morphology and thickness of the LaB_6 film remains intact throughout the fabrication process and even after the highly anisotropic dielectric etch. Thus, the chemically inert nature of the LaB_6 renders it a substrate which is appropriate for use as an etch stop during fabrication of nano- and micro-scale VEDs as well as an electrode for subsequent direct use in the final device. We note that the fabrication process described above is comprised of steps which are compatible with complementary metal-oxide-semiconductor fabrication, suggesting that future at-scale manufacturing of such LaB_6-containing devices is readily achievable with current foundry capabilities.

Finally, to test whether we could fabricate nanoscale, non-planar morphologies with LaB_6, we fabricated LaB_6 pyramids on a Si wafer using nanosphere lithography [6] for rapid proof of concept over a wide area. Representative SEM images of the resultant structures (Figure 3) reveal ordered arrays of LaB_6 pyramids over ~mm^2-scale areas. These features show great promise as field emitting tips. We are exploring extraction grids aligned to these features for high current density, nanoscale LaB_6 field emitters.

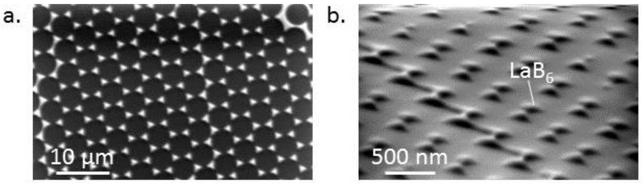

Figure 3. SEM image of pyramidal nanoscale LaB_6 tips.

Open Issues and Future Directions

Tiny, low-fill-factor grids on low work function electrodes show great promise for microscale vacuum electronics. One such example is the Field Emission Heat Engine, a novel type of heat-to-electricity converter which relies on strong fields near cold collector plates as well as low electron absorption by control grids [7]. We are actively solving two primary remaining challenges to implementation, which are avoidance of surface flashover/dielectric breakdown on these nanoscale, high aspect ratio dielectric supports due to high electric fields between LaB_6 and the grids and grid absorption of electrons by using lower fill factors and advanced grid morphologies.

Acknowledgements

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