Final Report for

GaN Vacuum Microelectronic Electron Emitter with Integrated Extractor

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Cold cathodes based on field emitters promise to provide high current density and high efficiency electron sources for a variety of applications from microwave power sources to flat panel displays. Vacuum microelectronic field emitters are field emitters of micron or sub-micron dimensions for low operation voltage (<100 V) that are fabricated utilizing microfabrication techniques common to semiconductor device fabrication. Vacuum microelectronic field emitters have been demonstrated in many materials—metals, semiconductors, and insulators—but all have had problems providing high current densities that are uniform or reliable. We hypothesize that GaN is an excellent material for field emitters for the following reasons: GaN is a ceramic semiconductor and as such is physically hard and should resist sputtering at low operating voltage thus improving reliability; GaN offers conductivity control thus the emission current level may be controlled by doping of the GaN; and GaN can be selectively grown to produce large, dense arrays of field emission pyramids. In this research program, we have investigated the growth and fabrication of GaN field emission arrays. The ultimate goal of this research project has been to integrate an extraction electrode with a field emission arrays to lower the operation voltage to practical levels.

A schematic of the originally proposed GaN-based field emitter with an integrated extractor is shown in Fig. 1. The emitter is formed by growing a heterostructure of GaN and AlN. The AlN serves as an insulating layer. The cathode is formed by etching through the AlN and into the GaN layer, forming a sidewall of masking dielectric (SiO_2) and finally growing the pyramids in the etched regions by metalorganic chemical vapor deposition (MOCVD). The growth is known as selective-area epitaxial regrowth because the growth occurs only in the unmask areas of the sample. The shape of the resultant growth is determined by selecting the growth temperature and pressure. The upper GaN layer is grown simultaneously with the pyramids and serves as the extractor electrode. The extractor electrode modulates the emitted current by varying the field at the emitter tip. Finally, contacts are placed on the GaN layers to apply bias. In this structure the anode, or collector, is a separate structure from the fabricated device.

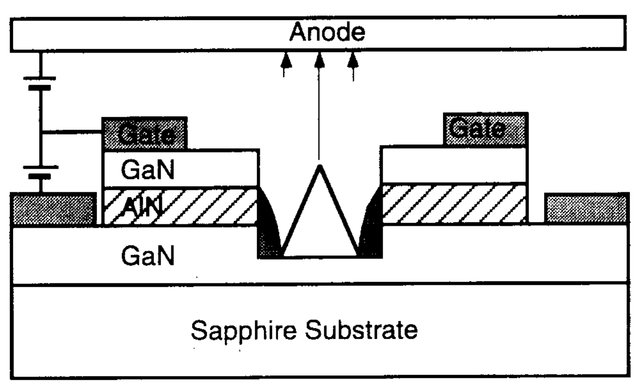


Fig. 1. Schematic cross section of proposed GaN field emitter.

The work on fabricating this emitter structure proceeded in several steps. First, demonstration of emission from GaN pyramids in a diode configuration (no extractor) was undertaken to show that electron field emission could be expected from GaN. Second, growth of pyramids in an etched GaN "pit" were investigated. Additionally, we also tested growth in "deep" (➢1 μm) etched areas as a thicker AlN layer is desired for lower extractor-cathode capacitance to allow higher speed operation. Growth was also attempted with the top metal contact in place to avoid realignment on a highly non-planar surface. The problems of these attempts will be discussed below. Finally, an improved self-aligned process was proposed and is under investigation.

Field emitters were successfully grown and tested in a diode configuration. In the diode configuration, the anode applies the bias to draw the electrons out of the cathode and collects the electrons. Our first attempt at measurement gave low current of 0.8 μA. Low emission current probably resulted from a large number of incomplete pyramids that did not contribute to the emission. Measurements of several other diode configurations with completed arrays yielded higher emission currents. The highest measurement was 80 μA over ~0.25 cm^2 array (tip density ~10^6 cm^{-2}) at a bias of 1100 V and an SEM of the array is shown in Fig. 2. This represents a significant improvement in emission current although it is still not believed that most of the pyramids of the array are emitting.

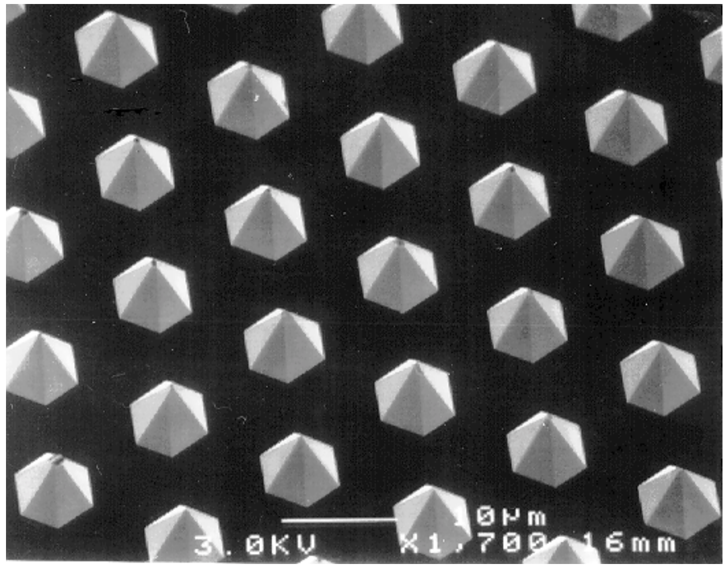


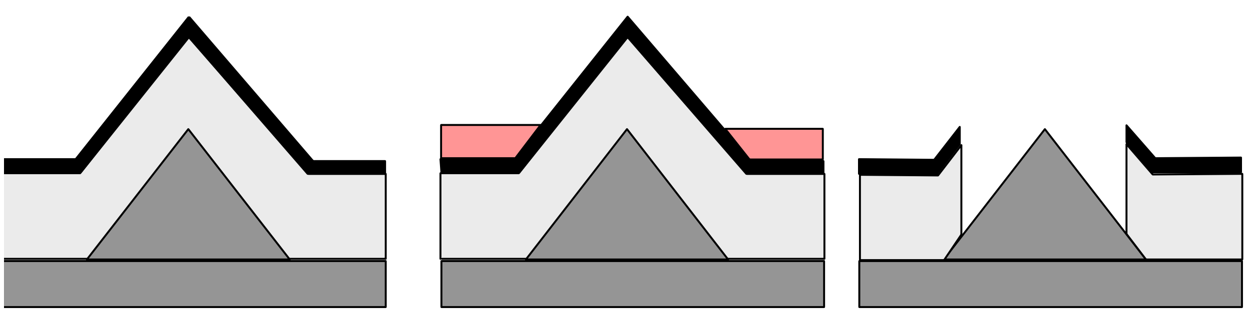
Fig. 2. Field emission array. Pyramids have diameter ~5 μm and are spaced on 11 μm centers.

Integration of an extraction electrode to lower the operating voltage and increase functionality then became the focus of our research. Selective-area regrowth experiments were carried out in which the pyramids were grown in "pits" etched into the GaN layer. The pits were etched by chlorine-based reactive ion etching (RIE) of the GaN. A dielectric sidewall to prevent growth on the vertical edges of the pits was used to prevent the pits from filling in and to force pyramid formation. The growth results were poor and apparently polycrystalline pyramids resulted. The poor growth is believed to be due to the poor morphology of the etched pit—both the bottom and the sidewall showed roughness. The poor morphology results from the physical nature of the RIE due to poor chemical reactivity of GaN. The use of AlN as the insulating layer was not attempted due to difficulty of growing AlN on GaN. Finally, the growth of pyramids in a deep etched area (>1 μm for pyramids having bases of 2 μm) was examined. Instead of etching a deep well, a thick SiO_2 layer was used to simulate the deep etch but allow high quality pyramids to be grown. This allows the effect of mask depth to be investigated separate from etching effects. Regrowth with thick (~1-3 μm) SiO_2 was attempted but did not produce good results. The reason for the poor regrowth with thick dielectric has not been determined. The difficulty of trying to grow high quality pyramids in the both the etched pits and deep mask layers lead us to temporarily abandon this approach and to try to use a different structure to realize the integrated extractor.

The modified structure replaces the AlN layer with SiO_2 and the GaN extractor is replaced by tungsten but otherwise the structure was as shown in Fig. 1. SiO_2 is chosen for its ease of processing and tungsten is chosen because as a refractory metal it can be introduced into the high temperature MOCVD reactor without melting. The tungsten and SiO_2 layers were then patterned by RIE. This structure is self-aligned in that the tungsten acted both as a regrowth mask and the extraction electrode. Use of tungsten as a regrowth mask had not been attempted before. The results of the experiment showed that tungsten was a poor mask for selective growth of GaN with the currently used MOCVD growth conditions. Finally, it was demonstrated that a thick SiO_2 layer coated with tungsten was unstable at the growth temperatures due to thermal mismatch and could not be used as a self-aligned mask and extraction electrode structure. Other mask schemes were tried but none yielded as good selectivity and ease of processing as SiO_2.

An improved fabrication process that would allow the growth of high quality pyramids and also allow the placement of an extraction electrode near the top of the pyramids was then developed. The pyramids are grown as they are for the diode arrangement. After the pyramids are grown, the regrowth mask (SiO_2) is removed and the process continues as shown in Fig. 3. The first step, labeled (a), shows a SiO_2 layer over the GaN pyramids and coated with a layer of nickel. The height of the SiO_2 may be varied to test the geometric dependency of emission, capacitance, and other operational parameters. The nickel will serve as an etch mask and the extractor electrode. Part (b) of Fig. 1shows a planarizing resist after plasma ashing has exposed the top of the tip and the correct opening diameter has been realized. The nickel is then etched away and serves as the mask for the etching of the SiO_2. The SiO_2 is etched first by RIE and then by wet chemical etchant to expose the GaN pyramid top. The RIE must not be allowed to reach the top of the pyramid as the RIE has been observed to dull the pyramid sharpness and that is the reason the etch must be finished by wet chemical means. Because the extraction electrode also serves as the etch mask, the structure is self-aligned and this should lead to high yield and uniformity across an array. The above process has been attempted once but was not successful because the RIE etch was not stopped in time to avoid damaging the tips. Work is ongoing to complete this process successfully.

In summary, the goal of our research was to integrate an extraction electrode on a GaN field emission array. The purpose of the goal was to lower the operating voltage of the array and demonstrate GaN as an excellent material for field emission devices. Because of growth difficulties, the originally proposed GaN field emission arrays could not be realized expediently. To make progress toward an integrated extractor, a technologically simpler structure utilizing SiO_2 dielectric and a self-aligned extractor metalisation was proposed and is in the process of being fabricated. Most importantly, selective-area regrowth of high quality GaN pyramid arrays has been demonstrated and characterized. Additional uses of selective area regrowth of GaN are being investigated as a result of this work.



(a) (b) (c)

Fig. 3. Improved process flow of field emitter with integrated extractor. a) GaN pyramid covered with SiO_2 and nickel. b) Planarization. c) After etch.