GaN field emitter array diode with integrated anode

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GaN field emission pyramids are grown by self-limiting, selective-area metalorganic chemical vapor deposition. The self-limitation provides the potential of high uniformity of the pyramids and the selective-area growth allows one to define regular arrays of GaN pyramids for field emitter arrays (FEAs). Fabrication of an integrated anode lowered the operating voltage of the FEAs by narrowing the anode-cathode distance compared to devices with an external anode. A maximum emission current of 0.15 μA/tip has been observed for voltages of 570 V with an emitter-anode separation of 2 μm. © *1998 American Vacuum Society.* [S0734-211X(98)07602-1]

I. INTRODUCTION

Field emission was observed from GaN field emitter arrays (FEAs) with integrated anodes. GaN is currently being investigated as a material for FEAs because it may possess certain material advantages for long-life and stable cold electron emitters. The results reported herein improve upon previous work on GaN FEAs that used an *external* electrode to extract and collect the field emitted electrons.[1,2] The large physical separation of the emitters and the external anode led to high impressed voltages (kV) necessary to induce emission. The high impressed voltages made the devices susceptible to damaging arcs and limited the current capability of the anode. The premature damage of the arrays limited our ability to investigate the physics and electrical properties of the FEAs. In response to this limitation, a design incorporating an *integrated* anode was proposed and successfully fabricated in order to lower the operating voltages of the FEAs. The anode design used in our work is similar to work presented by Yoon *et al.* for use on a planar cold cathode structure.[3]

GaN possesses a number of potential material advantages for vacuum microelectronics. The first advantage is the physical and chemical stability of GaN. It has a hardness comparable to diamond and a low chemical reactivity. These physical traits should lead to low sputtering rate *at low voltage* and an immunity to residual gas chemisorption. Secondly, in contrast to diamond, which is also being investigated actively for FEAs,[4] GaN can be easily doped *n* type to increase the electron concentration. In addition, because of the wide band gap of GaN, GaN-based devices can be expected to operate at higher temperatures and in higher radiation environments than lower band-gap semiconductors. Most importantly, the main advantage of GaN-based FEAs may be in the growth of the emitters themselves. Practical applications demand FEAs with a high degree of uniformity. Highly uniform GaAs pyramids have been produced by *selective-area epitaxy.*[5] Similarly, the selective growth of GaN had also been observed[6] and presented a method to produce GaN FEAs. When selective epitaxy of GaN is performed using two-dimensional circular mask openings of several microns in size, hexagonal pyramids result under a broad range of growth conditions.[2,6] The *self-limiting* growth of the field emitting pyramids by selective-area metalorganic chemical vapor deposition (MOCVD) has the potential to produce uniform arrays.[2] Finally, the ability to grade the group-III composition of the nitride semiconductor and to grow heterostructures could lead to the development of novel emitters as suggested by Shaw *et al.*[7]

Field emission was recently observed from GaN microscopic pyramids for the first time[1] and work by others on GaN FEA diodes has recently been reported.[8] The results of the reported works have shown relatively low current at high voltages. In our previous work, the anode structure limited the minimum voltage necessary to achieve field emission. A separate, external electrode was used as an anode with a minimum spacing of 0.1 mm. To decrease and provide better control of the separation, a design integrating the anode with the FEA was proposed. The anode was fabricated as an air-bridge over the field emission array. Thus, the anode can be controllably placed on the order of microns away from the pyramid tops.

The results of our first experiment on integrated-anode GaN FEAs are reported in this article. First, the fabrication of the field emitter arrays and integrated anode are detailed along with the self-limiting, selective-area growth of the GaN pyramids by MOCVD. Next experimental measurements of the physical and electrical characteristics of the FEAs are presented and the results discussed. Finally, a summary of the work is presented and directions for future work are briefly suggested.

II. EXPERIMENT

Fabrication of the GaN FEAs involved the following steps in a three mask process: patterning of the growth mask to define the arrays, selective epitaxy of the hexagonal GaN pyramids, and definition of the cathode mesa, contacts, and

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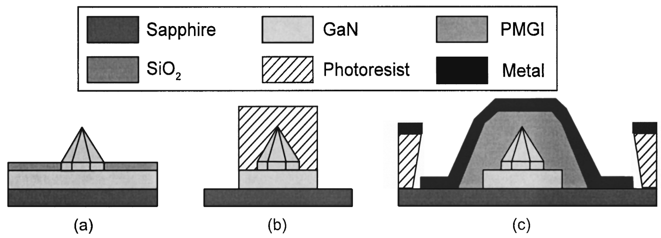

FIG. 1. Schematic of process flow of GaN FEA with integrated anode. Fabrication proceeds as shown from (a) to (c). (a) Selective-area growth of the GaN pyramids. (b) RIE etching of cathode mesas. (c) Anode air-bridge deposition and liftoff. Not shown is cathode contact metalization.

anode air-bridge. To begin, planar GaN films of nominal 2 μm thickness were grown by atmospheric pressure MOCVD using ammonia (NH_3) and trimethyl gallium (TMGa) as sources and hydrogen as the carrier gas. Growth conditions for planar GaN films on sapphire substrates have been published elsewhere.[9] The GaN layer must be conducting as it carries the current to the emitter tips from the cathode contact. The resistivity of this layer can be controlled by doping in order to provide current-limiting protection for the array.[10] On this layer, a mask film of SiO_2 was deposited by plasma-enhanced chemical vapor deposition (PECVD). The SiO_2 was patterned with arrays of 2 μm diameter holes on 10 μm centers by contact lithography and buffered HF etching. The GaN pyramids will grow selectively in these holes, as shown in Fig. 1(a). The circular openings allow the entire array to grow oriented to the crystal without having to identify and align to the substrate's crystal orientation. Devices were arranged in suites with four devices per suite. Each suite had a single-tip emitter, a 5-tip array, a 10-tip array, and a 40-tip array. Then, the sample was cleaned to ensure a low level of contamination. Finally, immediately prior to introduction into the regrowth reactor, the sample was given a brief dip in dilute buffered HF to ensure a clean GaN surface for epitaxial growth. In addition to the samples prepared for FEA fabrication described above, other samples were produced with multiple arrays of circular mask openings with varying opening diameters and spacing for growth rate characterization.

Epitaxial growth of GaN hexagonal pyramids for field emitter devices occurred through rapid vertical growth in the selective epitaxy mask openings and much slower growth on the pyramid sidewalls. When growth on the pyramid sidewalls was minimized through optimization of MOCVD growth parameters, the pyramids became self-limiting in size.[2,11] The selective epitaxy of the GaN pyramids were performed at 980 °C and 76 Torr reactor pressure using hydrogen as the carrier gas. TMGa flow of 18.4 μmole/min and NH_3 flow of 0.22 mole/min were used in the optimized growth. The self-limiting growth enables the fabrication of large arrays of uniform emitters despite growth rate nonuniformity that may occur in the MOCVD apparatus. Field emitter arrays for this study were obtained by this *self-limiting* growth process.

After growth of the GaN pyramids, fabrication proceeded with the definition of the cathode mesa as shown in Fig. 1(b). First, the selective-area growth mask was removed in an HF etch. Then, the FEA mesa was defined by $C1_2$-based reactive-ion etching (RIE) using photoresist as an etch mask. The GaN was etched down to the sapphire to isolate the cathodes and provide an insulating substrate for the anode.

The cathode contact pads and the anode supports were patterned next. Contact lithography and image reversal resist were used in a lift-off process to define the contact pads and anode air-bridge supports. The contact metalization layers were 100 Å of Ti and 5000 Å of Au. The excess metal was lifted off in acetone with brief ultrasonic agitation. The cathode contacts were completed by an alloying step in a rapid thermal annealer at 700 °C for 15 s.

The next mask step consists of opening the air-bridge supports and anode contact pads. Two layers of Nano™ PMGI SF15 positive photoresist[12] were spun on the sample. The thickness of the combined layers was approximately 6 μm measured from the sapphire. The anode-tip separation determined by this resist thickness would be approximately 1.7μm. On top of the PMGI, a positive resist was spun and patterned to expose the PMGI where the air-bridge supports were to be located. This positive resist served as the exposure mask for the deep ultraviolet (DUV) exposure ($\lambda=240$ nm) of the PMGI. The PMGI was then developed in Microposit® SAL®-101 developer.[13]

Finally, the air-bridge was patterned and metalized, and the PMGI was laterally etched from under the bridge to form the vacuum cavity Fig. [1(c)]. A trilayer photoresist system was used to provide a thick lift-off profile for the thick air-bridge metalization. The bridge metal was 200 Å of Ni and 1 μm of Au. The excess metal was lifted off in acetone with exposure to ultrasonic agitation. The final step in the process was the lateral etching of the PMGI sacrificial layer to undercut the bridge and open the vacuum cavity. The cavity was *not* sealed by this fabrication but the structures can easily be modified to accomplish integral cavity sealing.[14,15] The sample was cleaned and given a brief HF dip to remove any residual oxide from the surface before being transferred to the electrical testing systems.

Measurements were made of the physical characteristics of the devices at various stages of the fabrication. Scanning electron microscope (SEM) study was the best method to characterize the processing. Electrical measurements of the devices were performed in both high vacuum and ultrahigh vacuum (UHV) chambers. Measurements were made using dc voltage excitation with a picoammeter for current measurement and also using a curve tracer for swept voltage excitation and current measurement.

Electrical measurements were performed in two vacuum systems. The first system was a UHV system, pumped by oil-free sorption, ion, and Ti-sublimation pumps. The base pressure of the system was $\sim 9\times10^{-9}$ Torr. The sample was mounted on a ceramic chuck. The devices were gold-wire bonded to pins on the chuck and the pins connected to feedthroughs. The samples were out-gassed with the system bake at about 100 °C for 12 h. The second vacuum system used was a high vacuum system capable of reaching below

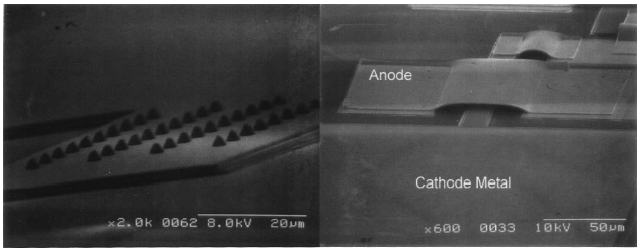

FIG. 2. SEM micrographs of GaN FEAs. Left shows a 4×10 array without anode and right shows a 1×5 array with anode completed.

the 10^{-5} Torr range. The chamber was allowed to pump overnight to achieve a low pressure. The advantage of this system was that it has micromanipulator probes that can be moved from device to device for rapid testing.

The measurement circuit consisted of a dc-voltage source (Bertan Associates Model 215), picoammeter (Keithley 486), and a current-limiting resistor (9.6 kΩ). The voltage was manually adjusted and a current reading was taken after the charging current decayed. The computer-controlled picoammeter would then take 25 readings, 0.5 s apart, which were averaged to produce a current value. The individual measurements were displayed in a histogram. If the distribution was not approximately Gaussian, the measurement was repeated. Finally, some of the devices were tested using a Tektronix curve tracer (model 576) to take swept current–voltage measurements of the diodes.

III. RESULTS

SEM characterization served as the best means to characterize the processing. The left micrograph in Fig. 2 shows a 4 × 10 array of GaN pyramids on the GaN mesa after the Cl_2 RIE. The right micrograph shows a completed single-tip GaN field emission diode. The tip was centered under the anode. The height of the mesa was measured by stylus profilometry to be 2.3μm. The left micrograph shows that the pyramids have a trapezoidal vertical cross section. The tops of the tips were mistakenly etched in the Cl_2 RIE. The removal of the tops of the pyramids should significantly decrease the field enhancement and threfore increase the turn-on voltage of the etched arrays compared to arrays with sharp tips. Because of the nonuniform thickness of the etch-mask photoresist, the resultant shapes of the etched pyramids were also not uniform resulting in poor device yield and reproducibility.

The anode-cathode separation, defined as the distance between the anode and the top of the GaN pyramid, was measured using the SEM. The distance from the base of the pyramids to the bottom of the anode was measured to be about 4.2 μm. the base of the pyramids has an inscribed radius, r, of 1 μm. From the geometry of the GaN crystal, the height of the completed pyramids is given by $h = 0.94(2r)$. Thus, the height of the completed pyramids was about 1.9 μm. The resulting anode-cathode separation was calculated to be 2.3 μm. The actual separation was larger due to the etching of the pyramids tops.

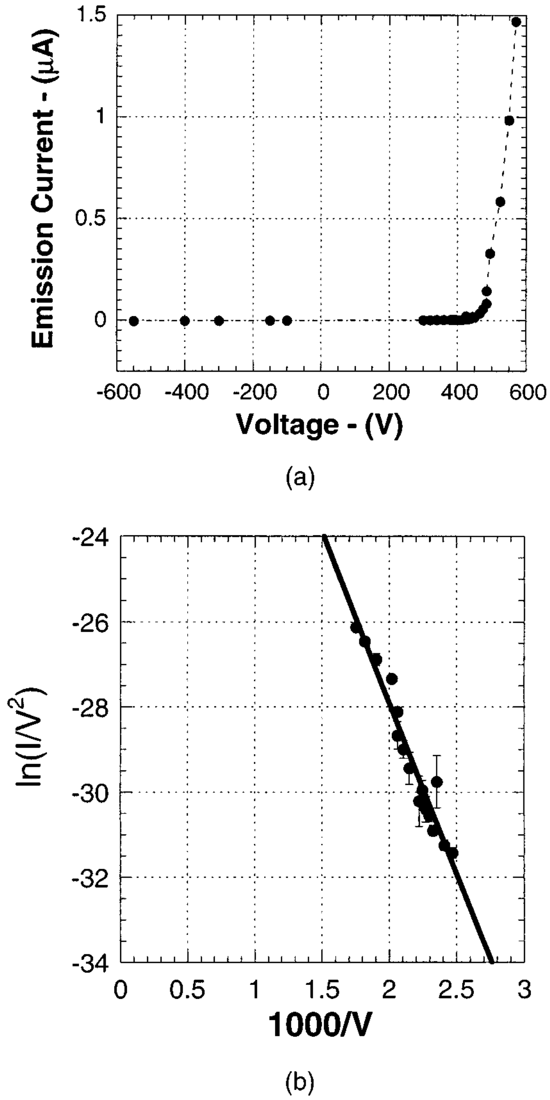

FIG. 3. Electrical measurement of 10-tip GaN FEA. (a) I–V characteristic. (b) Fowler–Nordheim plot.

Limited electrical measurements have been made of the field emitters in UHV. Evidence for field emission in this work is a linear Fowler–Nordheim (F–N) plot with a negative slope over several orders of magnitude of current and a negligible reverse-bias current. The F–N plot of the I–V characteristic of a 10-tip array suggests a field emission transport of the electrons as can be seen in Fig. 3. The F–N plot is approximately linear over about three orders of magnitude of current. The data shown in Fig. 3 were taken by applying a dc voltage as described above. As can be seen, the current is 0.15 μA/tip averaged over the array although there is no indication that all of the tips were contributing. Even though the current is small, the extraction voltage is the lowest yet observed from GaN. After reaching 570 V, the dc measurement circuit was replaced by the curve tracer. Increasing the voltage above 570 V caused an arc that destroyed the device under test. The sensitivity of the devices to arcing resulted in a poor measurement yield. In addition,

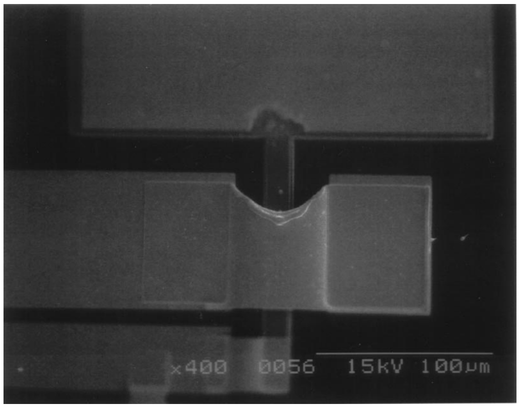

FIG. 4. SEM of damaged anode of a 5-tip GaN FEA diode. Magnification of the visible GaN pyramid showed no damage to the pyramid.

no quantitative statements could be made about the field enhancement factor, work function, or emitting area of the GaN pyramids tested because the precise geometry was unknown.

The above measurements were rather lengthy because they involved bonding the sample to a test chuck and a lengthy pump down of the UHV chamber. The available number of electrical feedthroughs allowed the testing of only one suite of devices per pump down. Quick testing of the devices was accomplished by the use of a vacuum system with micromanipulators. Devices measured in the dc mode mostly show an abrupt turn-on that in all cases resulted in a destructive arc as in the UHV system. Only one device yielded a very poor F–N characteristic. Some devices were measured using only the curve tracer swept to both positive and negative voltages. The resulting $I–V$ characteristic showed the expected capacitive current below some threshold voltage that varied from device to device between 400 and 700 V. At the threshold, a sharp increase of the *forward* current resulted but did not appear in the negative voltage polarity. The current did not appear to increase with time but if the peak voltage was left unchanged, a destructive arc would result in several seconds. A proper ''burn-in,'' or low current operation period, may alleviate these measurement difficulties.

Various kinds of damage resulted from the arcing of the devices. The most common failure mode was melting and destruction of the anode. If the current was limited with a large resistor, damage was ''slow'' and limited to the anode. An SEM image of a damaged anode is shown in Fig. 4. As can be seen, the anode apears to have begun to melt and deform. A GaN tip can be observed in the area where the anode deformed to expose the underlying structure. In all of the devices examined where slow anode damage had occurred, none of the GaN pyramids showed any damage. If a smaller resistor was used to limit the current, damage was seen in the underlying GaN and more extensive anode damage extending out to the contact pad was observed. Deflection of one device's anode was observed with cycling of the voltage from an arcing to an open state and back. The deflection was delayed with respect to the voltage change, indicating a possible thermal nature of the deflection and not electromechanical force.

IV. SUMMARY

We have presented the fabrication of a GaN-based FEA with an integrated anode. The emitters were produced by *self-limited*, selective-area epitaxial growth by MOCVD. The self-limited growth enhances the uniformity of the emitters. The integrated anode was fabricated as an air-bridge structure over the emitter array and its separation from the array can be controllably reduced to several microns or less. Electrical measurements have shown Fowler–Nordheim tunneling emission. Finally, study of damaged emitters showed that in current-limited arcing, the destruction of the device was due to the anode and not the cathode. We believe that sharper tips will lower the operating voltage such that the anode will not be destroyed under operating conditions. Future work on the GaN FEAs will focus on improved results from sharper tips under possibly lower voltages and investigation of emission from other nitride semiconductors.

ACKNOWLEDGMENTS

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