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M. Kildemo, Y.I. Levinsen, Séverine Le Roy, E. Sondergard. Staircase and saw-tooth field emission steps from nanopatterned GaSb surfaces. *Journal of Vacuum Science & Technology A*, 2009, 27 (5), pp.L18-L23. hal-00504472

**HAL Id: hal-00504472**

**<https://hal.science/hal-00504472>**

Submitted on 20 Jul 2010

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# Staircase and saw-tooth field emission steps from nanopatterned GaSb surfaces

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PACS : 68.37.Vj Field emission and field-ion microscopy, 68.37.Hk Scanning electron microscopy (SEM), 68.37.Lp Transmission electron microscopy (TEM), 61.46.Fg  
Nanotubes

Keywords : Field emission, nanopatterned surfaces, GaSb

## **Abstract**

High resolution field emission experiments from nanopatterned GaSb surfaces consisting of densely packed nanocones prepared by low ion-beam-energy sputtering is presented. Both uncovered and metal-covered nanopatterned surfaces were studied. The field emission surprisingly takes place by regular steps in the field emitted current. Depending on field, the steps are either regular flat plateaus or saw-tooth shaped. To our knowledge this is the first time that such results have been reported. Each discrete jump may be understood either as a resonant tunnelling effect causing the abrupt emission of a high aspect ratio single cone, or as a cascading effect where nearby cones switch on upon the on-set of the primary emitting cone with the highest field enhancement factor. The staircase shape may in both cases be understood from the spatial distribution of the aspect ratio of the cones. We find no evidence for a strong enhancement of the average field enhancement factor.

## **1 Introduction.**

Field emission phenomena are important for the understanding of electrical break-down phenomena which have been exploited for many years in terms of e.g. vacuum breakers and fast spark gap switches [1-3]. Recently, field emission has also become a major issue in high energy physics, as field emission initiated breakdowns in the next generation linear colliders may pose serious problems [4, 5]. Furthermore, field emission is also exploited in field emission displays ([3,6] references therein), or in field emission guns [7].

Previous research on the field emission properties of patterned surfaces, have mainly focused on the local field enhancement factor [8-10]. Recent studies of field emission from multilayer semiconductor structures [9] and on semiconductor nanopatterned surfaces [6, 10-13] suggest that quantum confinement can result in new features in the field emission process.

The experiments reported here on densely packed self-organized nano-pillars, indicate an overall Fowler-Nordheim like field emission (straight line in  $\ln(I/V^2)$ - $1/V$  coordinates) [1-3,6]. However, unexpectedly, the field emission proceeds in pronounced discrete staircase jumps.

## **2 Experimental**

The high resolution field emission scans were performed using a system nominally dedicated to high voltage break-down studies [14]. High resolution in terms of electric field steps, was obtained by applying voltages from approximately 1 kV to 9 kV (depending on the tip-sample distance), in steps of 1V. Furthermore, by using larger anode-cathode (tip-sample) distances, the experiment also allowed for probing larger surface areas (i.e. probing a larger number of emitters). All field emission measurements were performed in a vacuum better than  $5 \cdot 10^{-8}$  Torr. The applied field was typically in the range 20-200 MV/m, (applying 1-6 kV

voltages) with field steps of typically 20-200 V/m (voltage steps of 1 V). The first few scans often resulted in a conditioning type of event, with a small current burst. For each sample three different regions were studied by moving the sample relative to the tip. At the end of the experiments the sample was imaged by SEM.

The field emission experiments were performed by mounting the sample on a Cu sample holder, and attaching it with stainless steel screws to make a good front surface contact. The hemispherically shaped anode tip had a diameter of 2.3 mm. All field emission experiments were performed by avoiding tip-surface contact prior to the experiment. The relative movement of the tip was carefully calibrated *ex-situ*. The electric fields were estimated by first approaching the tip to a reasonable distance to the surface. Then multiple field emission scans were performed by approaching the tip in known distance steps closer to the surface. The tip-surface distance and the field emission factor ( $\beta$ ) could then be estimated from Fowler-Nordheim analysis of such multiple scans. Finally the estimated distance was also verified by moving the tip all the way into contact with the surface at the end of the experiment.

Three nanopatterned GaSb samples produced in similar conditions were investigated. All samples were prepared by low-ion-energy sputtering [15-17]. The sputtering was performed by Ar<sup>+</sup> bombardment of a clean (double side polished) Te-doped GaSb(100) wafer, leading to surfaces consisting of self-organized GaSb. The cones have an average of 6 nearest neighbours, a typical separation of 80 nm and height of approximately 250-300 nm [15,16].

The first sample was an uncovered nanopatterned GaSb sample. The second nanopatterned GaSb sample was additionally coated by 100 nm of Mo, in order to insure a good surface conductivity. The third nanopatterned sample was coated with 50 nm of Mo.

### 3 Results

The Figure 1a shows the SEM image of the uncovered nanopatterned GaSb surface prior to the field emission experiment. Figure 1b shows a cross section SEM image of a similar sample. The diameter of the tip of the cones appears to vary from cone to cone. Typical dimensions are 5-15 nm, but sometimes as low as 2 nm is found. The Figure 1c shows the SEM image of the nanopatterned GaSb surface covered with an approximately 100 nm thick Mo layer. The deposited metal accentuates the tip of the cones, while the main features of the nanostructure appear intact. The Mo ball on the top of the cones has typically a diameter of approximately 100 nm, making a total cone height of 350-400 nm.

Figure 2 show multiple field emission scans from the uncovered nanopatterned GaSb sample, with decreasing tip-sample separation from the right to the left curve, respectively. The general trend of the field emission follows the Fowler-Nordheim emission theory, with additional features at higher field emission currents, as discussed in field emission studies from other semiconductor surfaces [6,11-13]. The most interesting feature of Figure 2, is the observation of the discrete jumps in the field emitted current, and the staircase shaped field emission. Figures 3 and 4 show the high resolution field emission scans from the nanopatterned GaSb surface covered with a 100 nm thick Mo layer. The scans were recorded at two different areas on the surface, and with two different gap distances. The discrete current steps are clearly observed. These steps are initially well separated straight staircase steps. At higher field emission, the step separation becomes shorter and shorter, and the emission appears to drop in between each step leading to a saw-tooth shape. The inset in Figure 4 shows that these features are consistently present at higher emission currents, but that the 1 V step resolution eventually cannot resolve the fine structure of the steps at higher currents.

The cross-section SEM images resulted in a rough estimate of the radius of the tip of a single cone larger than 2-5 nm, while the cone height is estimated to approximately 250 nm (always less than 300 nm). In terms of a single cone “micro-protrusion model” [1], the field enhancement factor may be estimated from  $\beta=0.5*h/r+5$ , where h is the total height of the cone, and r is the radius of the tip of the cone. For the uncovered nanopatterned GaSb surface,  $\beta$  is then predicted to 50-70, while it was predicted to  $\beta=400/50+5=11$  for the 100 nm Mo covered surface, and roughly  $\beta=350/25+5=15$  for the 50 nm covered surface.

The experimental average field enhancement factor calculated from the slope of the Fowler-Nordheim plot ( $\ln(I/E^2)$  vs  $1/E$ , where I is the field emitted current and E is the electric field) for the uncovered nanopatterned GaSb surface was estimated to typically 40, using for simplicity a workfunction of 4.5 (the electron affinity of GaSb is nominally reported to be 4.06 eV). The E-field was calculated from  $V/d$ , where V is the applied voltage, and d is the tip-surface distances (d). The tip-surface distance (d) and the voltage step sizes for the multiple traces from left to the right in Figure 2, were approximately 44  $\mu\text{m}$  and 10V, 40.5  $\mu\text{m}$  and 10 V, 36  $\mu\text{m}$  and 33.5  $\mu\text{m}$  and 5V respectively. In particular, using the calculated maximum electric field, it is observed that the on-set of field emission appears around 30-40 MV/m, while it reaches 1 nA around 40-50 MV/m.

The field emission scan for the 100 nm covered nanopatterned GaSb surface also follow a Fowler-Nordheim emission trend, see Figures 3 and 4. The field enhancement factor ( $\beta$ ) was estimated to 30 on the first measurement area with a small gap (approx. 13  $\mu\text{m}$ ), see Figure 3, and to  $\beta=250$  for the second measurement area with a much larger gap (approx. 168  $\mu\text{m}$ ), see Figure 4, using a work function of 4.6 eV.

The field emission data from the 50 nm Mo coated nanopatterned GaSb, recorded with 1V steps also showed a pronounced staircase emission. The field emission enhancement

factor was here estimated to 80, a factor 5 higher than expected from the simple micro-protrusion model.

It is noted that further increasing the field emission currents eventually resulted in sparks and major surface damages, as was observed from SEM after the field emission measurements.

#### **4. Discussion**

There appears overall not to be a major enhancement of the field enhancement factor from low ion-beam energy nanopatterned GaSb surfaces, while a tendency of an increased field enhancement factor for the Mo coated nanopatterned surfaces was found.

The staircase field emission is a new and interesting phenomenon. The reason why this effect have not previously been observed may be due to the lack of high resolution field emission data in previous studies [6, 10-12]. It could also stem from a unique coupling of the geometric arrangement and the material investigated here. It must be emphasized that the staircase field emission is observed from three different samples with a different surface nature, indicating that it may be a general feature for such nanopatterned samples.

In order to explain the data reported here several points have to be addressed; the overall staircase shape of the field emission scan, the shape and evolution of each step and the transition to a saw-toothed shaped form at higher fields. Clearly, interpretations can be based either on the local emission from a single cone or on collective emission from a distribution of emitters.

General models for the field emission from semiconducting nanoprotrusions have recently been discussed [11,13,18]. In particular, multiple barrier systems were calculated to result in structures in the field emission spectra such as emission current peaks and negative differential conductance [13]. Experimentally, a few discrete steps have also been observed



from single multi-walled carbon nanotubes [19, 20], while a few oscillations in the emission current may be observed from the measured field emission scans from GaN quantum dots [13]. The latter reports does not offer a direct explanation for data reported here.

The regular and reproducible steps in the emission current observed in this work, evokes the possibility of resonant quantum tunneling from a single emitter. Such a case has been reported from low temperature field emission studies of quantum structures, using a Scanning Tunneling Microscopy tip [21]. Taking into account the large dimensions of the cones, it is unlikely that room temperature quantum effects cause such a regular staircase structure in the field emission. However, a low dimensional structure with a reasonable separation of energy levels could exist at the tip of the cones. Recent observations have indicated the occurrence of a Ga rich zone at the cap on nanopillars similar to those investigated in this work [15]. The near spherical cap may work as a quantum sized dot (diameter of less than 5 nm), and depending on the effective electron mean free path, could thus play an important role in terms of resonant tunnelling trough quantum levels in a multiple barrier system [13,18]. Nevertheless, further complication arises from the experimental observations of the Mo covered nanopatterned surface. In the latter case, the Mo ball appears to surround the Gallium rich cap, see Figure 1c, possibly making more barriers, of which only the Ga rich cap may have a number of quantized states.

The staircase field emission is much more likely to be the result of sequential on-set of field emitting cones due to a discrete distribution of the field enhancement factors (i.e. aspect ratios), rather than a result of a single emitter. In particular, the area of constant field (within 99% of maximum field) scales in the current set-up roughly as  $\pi d^2$  (using a simple image charge model), where  $d$  is the tip-sample distance, resulting in a large sample area  $>3500 \mu\text{m}^2$  for the clean nanopatterned GaSb. The area of constant field (within 99%) for the Mo covered nanopatterned GaSb  $> 530 \mu\text{m}^2$  (Figure 3), and an area  $>80000 \mu\text{m}^2$  for the second spot on

Mo-covered nanopatterned GaSb (Figure 4). Even though the field is radially distributed on the sample surface, one is effectively uniformly probing a large number of cones (typical cone density of  $200/\mu\text{m}^2$ ). The fact that one may observe discrete steps from such a large distribution, is then possibly a result of only probing the high end of the distribution of field enhancement factors ( $\beta_i$ ). The probability of switching on an emitter increases rapidly upon increasing the electric field, since one is then probing closer to the centre of the distribution of  $\beta_i$ . The observed reduction in the step length upon increasing voltages on the anode tip could thus be understood as an increased probability of on-switching of emitters upon increasing the electric field.

The shape of each step is abrupt in terms of the experimental resolution. The “sudden” on-switch of an emitter could possibly be due to a resonant tunnelling through an intermediate defect band or a low dimensional quantized state [13], or simply a dielectric breakdown through a dielectric oxide layer [2]. Another hypothesis not implying quantum resonance emission phenomena, is based on that the on-set of a single emitter, with a favourable high field-enhancement factor, results in a cascading effect of on-switching of nearby emitters through the local field enhancement of nearby emitters created in the emission process started by the first emitter (e.g. the prime emitter goes to a relative positive potential w.r.t. the secondary emitters). The latter hypothesis may be investigated by studying the temporal characteristics upon each voltage step.

In any of these models, the structure and morphology of the nanocone/nanopillar and its surface termination would be important. In particular, it has been observed from Transmission Electron Microscopy (TEM), that the cones are surrounded by a layer of a-GaSb and an outer layer of GaSb-oxide. Amorphous-GaSb has a lower gap ( $<0.2$  eV) than c-GaSb (0.725 eV), while the oxide is a wide-band gap semiconductor with a gap of approximately 3.7 eV (from optical measurements). Both tunnelling through an intermediate

band or a dielectric breakdown through e.g. the 5 nm outer dielectric GaSb-oxide may be at the origin of the sudden on-switch of a single emitter, although the observations from the Mo covered cones further complicates the models.

Remarkably, the steps exhibit flat plateaus for lower emission currents, and a saw-tooth form for higher currents. The flat emission of each staircase could be the result of an emission-charge effect in the nano-sized emitter, i.e. due to the limited electron reservoir in the emitting cone [13]. At larger emitted currents, the emission decays on each staircase, giving the saw-tooth form observed from the field emission scans, leading to a local negative derivative in the VI curve (also denoted negative conductance [18]). The emitting cone can be assumed to heat up during field emission, especially for higher currents. This would affect the Gallium rich cap at the top of the tip by changing the phase of the tip of the cone (e.g. towards a liquid Gallium cap). Evidently, such an event would modify the transport properties of the cone, possibly causing the decay of the emitted current on a staircase. Such a phase transition between the solid and the liquid state has been reported for Ga in terms of a change of optical properties [22].

The height of each step in terms of emission current is observed to increase as a function of emission current, which is consistent with the pre-factor of the field squared in the Fowler-Nordheim model. In the cascading model, higher emission currents would be expected to e.g. generate higher changes in the distribution of the local field, possibly increasing the probability for on-switching of nearby emitters.

## **Conclusions**

The field emission from nanopatterned GaSb surfaces consisting of densely packed nanocones follows initially and overall a Fowler-Nordheim like emission behaviour, with generally modest field enhancement factors. A new and interesting phenomenon was revealed;

at high voltages and small voltage steps the field emission showed pronounced staircase emission as a function of applied voltage. The staircase field emission is a striking new feature which appears to be linked to the nanopattern. Further research is needed to settle if these observations are general properties of nanopatterned surfaces, or specific to GaSb based materials. The origin of the staircase field emission clearly needs further experimental and theoretical investigations.

The proposed models for the field emission staircases observed in this work, attribute the field emission to a statistical spatial distribution of the field enhancement factors, while the overall field emission follows the Fowler-Nordheim trend. Such issues, may also be of importance in break-down studies related to linear collider accelerators

## **Acknowledgements**

The authors are grateful to S. Hagen and J. C. Walmsley at the NTNU for help with performing the SEM images.

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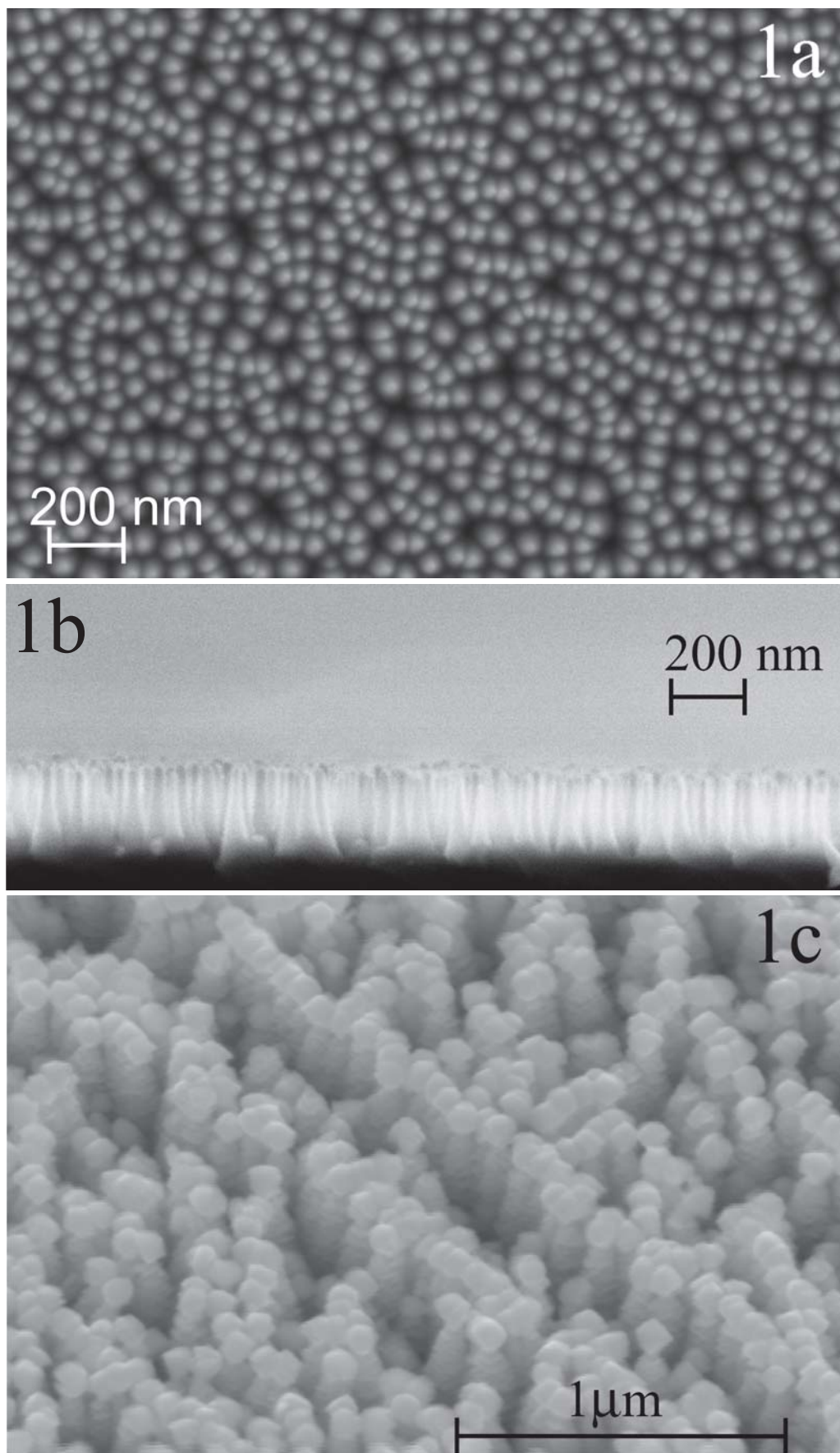
## Figure Captions

**Figure 1.** SEM images of the samples studied by field emission. Figure 1a shows the uncovered nano-structured surface, recorded at normal view. Figure 1b shows the cross section SEM image of a GaSb sample produced under identical conditions. Figure 1c shows the SEM image of the 100 nm Mo covered nanopatterned surface, tilted sample view.

**Figure 2.** Field emission measurements from uncoated nanopatterned GaSb, see Figure 1a and 1b. The tip-surface distance and the voltage step sizes for the traces were approximately 44  $\mu\text{m}$  and 10V (right curve, open squares), 40.5  $\mu\text{m}$  and 10 V (full squares, blue curve), 36  $\mu\text{m}$  and 5 V (open circles, red curve), and 33.5  $\mu\text{m}$  and 5 V (left curve, open triangles, green).

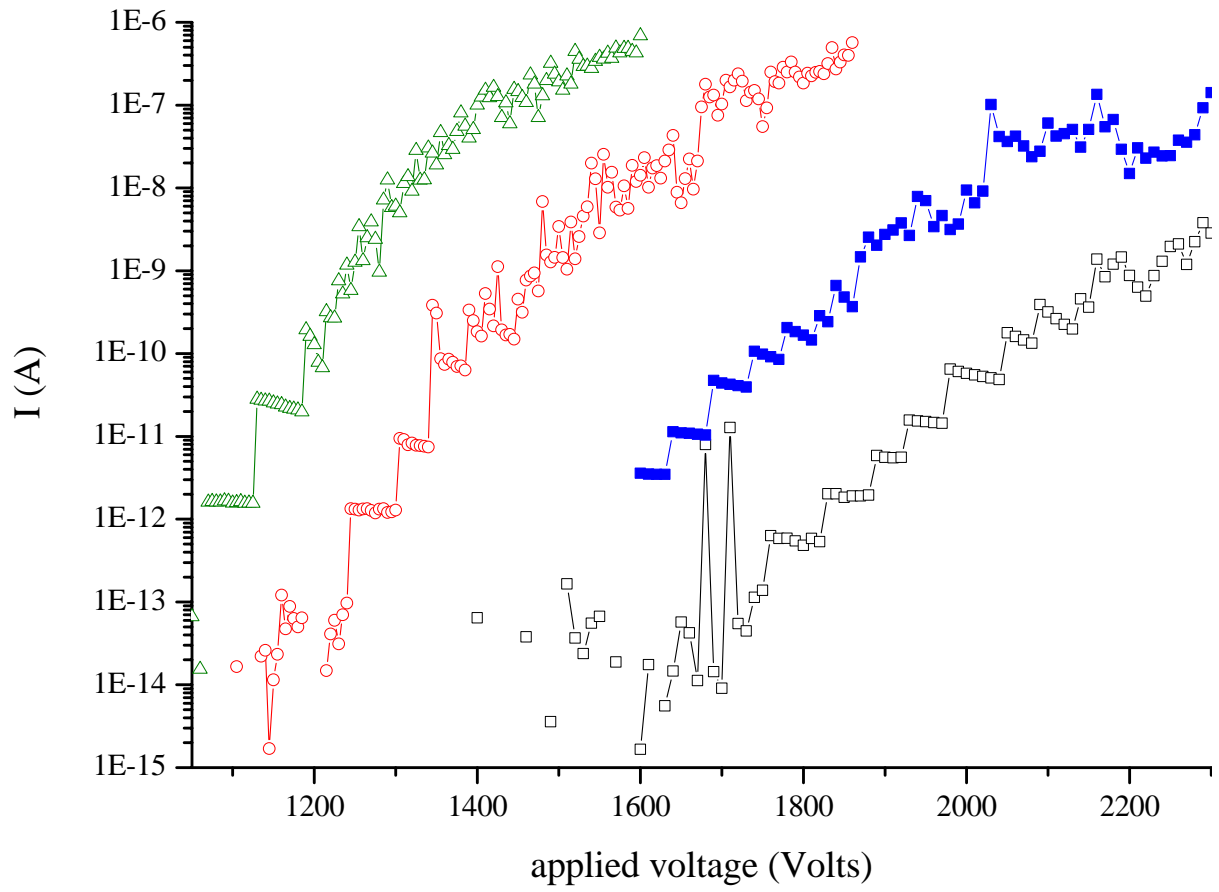
**Figure 3.** Field emission measurements from 100 nm Mo coated nanopatterned GaSb (GaSbn133), region 1. The gap-distance was approximately 13.1 microns, resulting in an on-switch at approximately 110 MV/m, and 1 nA emission at 142 MV/m. The resolution was 1V steps. A SEM image of the surface is shown in Figure 1c.

**Figure 4.** Field emission measurements from the 100 nm Mo coated nanopatterned GaSb, on a different spot from the field emission scan in Figure 3. (GaSbn133, spot 2). The tip-sample distance was here estimated to 168  $\mu\text{m}$ . The emission on-set was thus here estimated to 20 MV/m while 1 nA was reached at 26 MV/m. A representative SEM image of the surface is shown in Figure 1c.

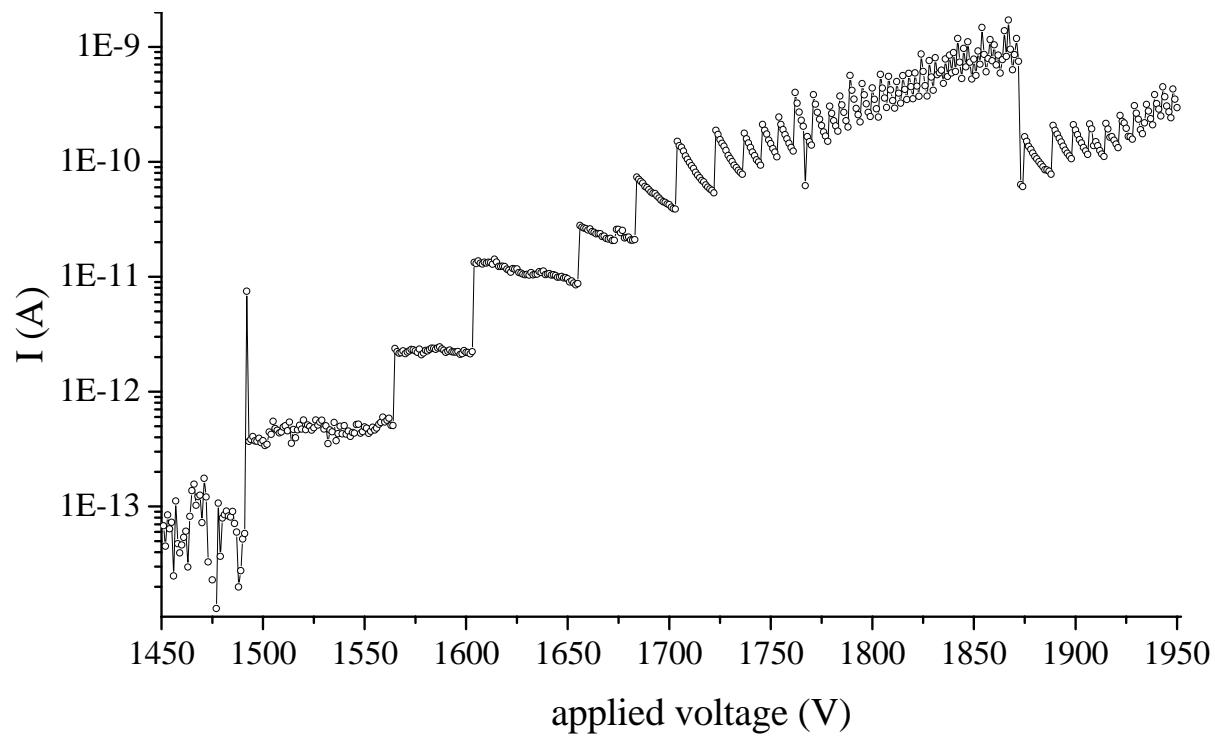


**Figure 1.**

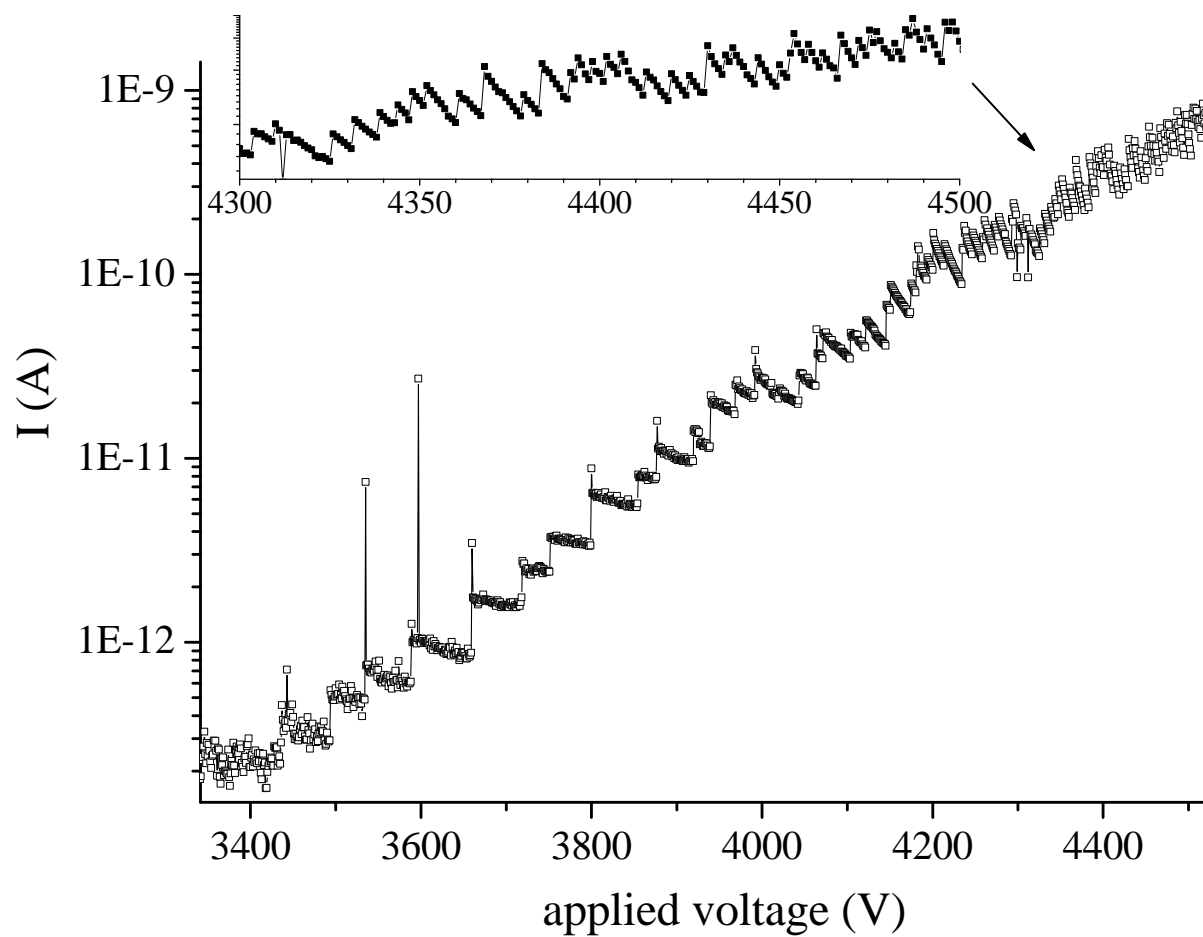




**Figure 2.**



**Figure 3.**



**Figure 4.**