Characterization of InSb nanopillars for field emission applications

F Giubileo\textsuperscript{1,*}, E Faella\textsuperscript{2}, A Pelella\textsuperscript{1,2}, A Grillo\textsuperscript{1,2}, M Passacantando\textsuperscript{3}, R LaPierre\textsuperscript{4}, C Goosney\textsuperscript{4} and A Di Bartolomeo\textsuperscript{1,2}

\textsuperscript{1}CNR-SPIN Salerno, via Giovanni Paolo II n. 132, Fisciano 84084, Italy
\textsuperscript{2}Physics Department “E. R. Caianiello”, University of Salerno, via Giovanni Paolo II n. 132, Fisciano 84084, Italy
\textsuperscript{3}Department of Physical and Chemical Science, University of L’Aquila, and CNR-SPIN L’Aquila, via Vetoio, Coppito, L’Aquila 67100, Italy
\textsuperscript{4}Department of Engineering Physics, McMaster University, 1280 Main Street West, Hamilton, Ontario L8S 4L7, Canada

\textsuperscript{*}E-mail: filippo.giubileo@spin.cnr.it

Abstract. A piezoelectrically driven metallic nanoprobe is installed inside a scanning electron microscope to perform local characterization of the field emission properties of InSb nanopillars. The tip-shaped anode can be precisely positioned at sub-micron distances from the emitters to collect electrons from areas as small as 1µm\textsuperscript{2} under the application of an external bias up to 100 V. Current-voltage characteristics are measured for cathode-anode separation down to 500 nm and are analyzed in the framework of the Fowler-Nordheim theory. We give estimation of performance parameters such as the field enhancement factor and the turn-on field and their dependence on the cathode-anode separation distance. We demonstrate the time stability of the emitted current for several minutes. Finally, we perform a finite element electrostatic simulation to calculate the electric field in proximity of the nanopillars and we evaluate the effective emitting area as well as the screening effect due to presence of other pillars in close vicinity. We show that InSb nanopillars are very stable emitters that allow current density as high as 10\textsuperscript{4} A/cm\textsuperscript{2} and excellent time stability, crucial characteristics to envisage device exploitation.

1. Introduction
Field emission (FE) is a quantum tunnelling phenomenon enabling electrons to escape from a metal (as well as from a semiconducting) surface and be emitted in the vacuum by travelling through the surface barrier under the application of a strong electric field (typically of the order of 10\textsuperscript{7}-10\textsuperscript{8} V/cm) [1]. The potential barrier at the metal-vacuum interface is modified by the electric field, becoming triangular and thinner, so that the effective barrier results lower (see figure 1a). For instance, it has been evaluated that for a metal surface with work-function, i.e. the potential difference between the Fermi level and the vacuum, $\varphi = 4.5$ eV, the width of the potential barrier depends on the applied electric field, such that it can reduce from 4.5 nm to 0.5 nm when the field is increased from 3\texttimes10\textsuperscript{7} V/cm to 3\texttimes10\textsuperscript{8} V/cm [2].

The FE phenomenon can be exploited for several applications related to the development of electron or x-ray sources [3–5], microwave amplifiers [6], vertical field effect transistors [7], memory devices [8], flat panel displays [9], etc. Moreover, the field emission properties are mostly related to the cathode
material, geometrical shape, aspect ratio and to the presence of surface states. Consequently, in recent
years, several one-dimensional (1D) and two-dimensional (2D) nanostructures have been investigated
as FE devices to profit from the important field enhancement in proximity of an apex. Experiments have
mostly dealt with carbon nanotubes [10–17], nanowires [18–21], nanopillars [22–24], nanoparticles
[25–27], graphene flakes [28–30], transition metal dichalcogenides [31–36], etc.

From a theoretical standpoint, FE has been initially described by the Fowler-Nordheim (FN) theory
[37], a one-dimensional (1D) free electron model developed to evaluate the tunnelling probability for
an electron escaping from a planar metallic emitter under uniform electric field and at 0 K temperature.
Despite its simple formulation, this model provides a formula for the FE current (Equation 1) that has
been widely applied to several experimental conditions to verify the occurrence of the phenomenon, at
least in a first approximation. Within this theory the FE current is expressed as:

\[
I = S \cdot A \frac{1}{\phi^2} \beta^2 \frac{V^2}{d^2} \exp \left( -B \frac{\phi^3}{2\beta} \frac{d}{V} \right)
\]

where \(A = 1.54 \times 10^{-6} \text{AV}^{-2} \text{eV}^{-2}\) and \(B = 6.83 \times 10^9 \text{eV}^{-3/2} \text{m}^{-1} \text{V}^{-1}\) are constants, \(S\) is the emitting
surface area, \(\phi\) is the work function of the emitter, and \(E_{\text{local}} = \beta V/d\) is the local electric field that
depends on the applied voltage \(V\), on the cathode-anode separation distance \(d\), and on the field
enhancement factor \(\beta\) due to the emitter shape. The theory has been revised by Murphy and Good [1]
to include the tunnelling barrier modification, in shape and size, due to image effects. The main differences
arising, despite a very similar formal equation, is related to the prediction of current values that are up
to 300 times greater than values expected from FN theory [38,39].

In this paper, we investigate the FE properties of InSb nanopillars by means of a tip-shaped anode
setup arranged inside a scanning electron microscope (SEM), in which a tungsten tip with curvature
radius of about 100 nm is precisely positioned at a distance of the order of 1 \(\mu\)m above the emitting
surface. We characterize individual nanopillars, with diameters of 400 nm and 600 nm, evaluating the
field enhancement factor and the turn-on field. We also performed electric field simulations to estimate
the expected field enhancement due to the nanopillar geometry and to identify the effective emitting
area.

Figure 1. (a) Energy band structure with bending of the vacuum barrier in presence of applied electric
field. (b) Schematic of FE setup inside SEM chamber.

2. Experiment
Indium antimonide (InSb) is a semiconductor of the III–V family, with small (direct) band-gap of 0.17
eV at room temperature. The nanopillars have been fabricated starting from an InSb thin film grown by
molecular beam epitaxy. Nanopillars have been successively obtained by standard electron beam
lithography and reactive ion etching techniques. Detailed information about the fabrication process are
already published [40].
The FE measurements are performed inside the vacuum chamber of a Zeiss LEO 1530 SEM endowed with two tungsten probe tips (with curvature radius \(~100\ \text{nm}\)) working as nanomanipulated electrodes. In particular, one probe (cathode) is connected to the emitter, while the other tip (the anode) is positioned above the emitting surface to collect the electrons. Electrical measurements are performed by applying a positive bias up to \(+120\ \text{V}\) on the anode and by measuring the current flowing through the FE device with precision better than 0.1 pA. A schematic of the FE setup is shown in figure 1b.

In figure 2, we report the FE current-voltage (I-V) characteristics measured for two different InSb nanopillars arrays, with different top diameter (D) and pitch. Electrical measurements have been performed by positioning the tip-anode 1000 nm above the emitting surface (the top surface of the nanopillar) approximatively in correspondence of the center of one nanopillar. Figure 2a refers to the current measured for nanopillars having D = 600 nm and pitch of 1500 nm. We performed a bias sweep up to 120V and we observed that the current remains at the value of the floor noise of the setup (well below 1pA) till the bias reach approximatively 75 V. Then, the measured current keeps increasing exponentially for about four order of magnitudes up to 10 nA for applied bias of 115 V. We estimate the turn-on field \(E_{\text{on}} = V_{\text{on}}/(d \cdot k_{\text{tip}}) \approx 49\ \text{V}/\mu\text{m}\) (defined as the applied field necessary to extract a current of 1 pA) where \(V_{\text{on}}\) is the voltage to which the FE current is 1 pA and \(k_{\text{tip}}\)(\(~1.6\)) is a geometrical factor to take into account the tip-shaped anode configuration [14]. According to equation (1), FE current can be identified when \(\ln\left(\frac{I}{V^2}\right)\) versus \(1/V\), the so-called FN plot, has a linear behaviour, with a slope \(m = -(Bdq^{3/2})/\beta\). The lower inset in Figure 2a shows that FN plot is linear confirming the FE nature of the measured current. We also extract the field enhancement factor as \(\beta' = \beta \cdot k_{\text{tip}} \approx 60\) by including the effect of the anode geometry [14]. Similarly, in Figure 2b we show the FE current measured for a nanopillar from the array with top diameter D = 400 nm and pitch 2500 nm, by placing the tip anode at the same separation distance \(d = 1000\ \text{nm}\). In this case, the turn-on voltage as well as the turn-on field are lower \((V_{\text{on}} \approx 55\ \text{V}, E_{\text{on}} \approx 34\ \text{V}/\mu\text{m})\), while the field enhancement factor is \(\beta' \approx 75\). This variation of the FE performance parameters, \(E_{\text{on}}\) and \(\beta'\), can be explained as the result of the different geometry for the two nanopillar arrays under investigation. Indeed, a smaller top surface diameter D corresponds to a larger aspect ratio, and consequently to a larger enhancement factor at the emitter. Similarly, a larger pitch, i.e. a larger separation between the nanopillars causes a reduced electrostatic screening and consequently a lower field is necessary to extract current from the emitter [13,41].

![Figure 2. I-V characteristics measured for nanopillar with top diameter D = 600 nm (a) and D = 400 nm (b). Solid lines represent the fit of experimental data with equation (1). Insets in the left upper corner show SEM image of the InSb array. Insets in the right lower corner report the FN plots with linear fit.](image-url)
3. Simulations
To confirm and quantify this explanation, we also performed electric field simulation using COMSOL Multiphysics software for finite elements calculations. We simulated the electric field in proximity of the nanopillar due to an applied bias up to 100 V on the tip anode with spherical apex and curvature radius 100 nm, at a separation from the top surface of the pillar of 1000 nm. The geometrical configuration and the resulting electric field is presented in figure 3a and 3b for the D = 600 nm nanopillar and D = 400 nm, respectively. The color scale shows that the highest value of the electric field is calculated at the borders of the top surface of the nanopillars. We show in Figure 3c and 3d the profile of the electric field on the top of the nanopillar for the two configurations, the intensity of the electric field being measured on a line with 10 nm step. It is evident that for D = 400 nm and pitch of 2500 nm the electric field at the apex of the pillar is significantly higher. Moreover, by taking into account the symmetry of the problem, we can calculate the total FE current as the sum of contributions due to annular concentric areas (expressed in nm$^2$), $S_i = \pi \cdot [(i \cdot 10)^2 - ((i - 1) \cdot 10)^2]$, with $1 \leq i \leq 20$ (see figure 4a). Consequently, according to equation 1, the total current is given by

$$I = \sum_{i=1}^{20} I_i = \sum_{i=1}^{20} S_i \cdot a \phi_i^{-1} E_i^2 \exp(-b \phi_i^{3/2} E_i^{-1})$$

where $I_i$ is the current emitted by the annular surface $S_i$ with fixed width 10 nm and $E_i$ is the electric field calculated in that position.

![Electric field simulation](image)

**Figure 3.** Electric field simulation performed by COMSOL Multiphysics software for the D=600 nm array (a) and for D = 400 nm array (b), fixing the tip anode at $d = 1000$ nm from the emitting surface. The values of the electric field on the top surface of the nanopillar are calculated with a step of 10 nm for D = 600 nm nanopillar (c) and for D = 400 nm nanopillar (d).
From this analysis we obtained that all the current is emitted from the top border of the nanopillars. More precisely, in the case of nanopillar with $D = 400$ nm the current is emitted from the outermost annular area, $S_{20} = \pi \cdot 3900 \text{ nm}^2$, corresponding to a current density of the order of $10^4 \text{ A/cm}^2$. Indeed, in Figure 4b, we show the ratio $I_i/I_{20}$ for each annular area $S_i$, from which it is evident that all other annular areas give a contribution to the total current that is several order of magnitudes smaller with respect to $I_{20}$. Also, from the closest area ($S_{19}$) the emitted current is more than four orders of magnitude smaller than $I_{20}$.

![Figure 4](image)

**Figure 4.** (a) Schematic of the top diameter of the nanopillar with $D = 400$ nm. Each annular area has fixed width of 10 nm. Color bar gives indication of the electric field intensity along the radius. (b) Intensity of the emitted current with respect the current $I_{20}$ emitted from the most external annular area.

We finally observe that the field enhancement factor that we extracted from the experimental data within the FN framework is much larger than the value obtained from the simulation. This discrepancy can be ascribed to the presence of surface roughness and/or local nanoprotrusions that can significantly increase the local enhancement of the electric field [13,42] and that are not included in the simulation model.

4. Conclusions

We performed field emission experiments on InSb nanopillars using a nanomanipulated tungsten tip as anode to collect the electrons emitted from individual nanopillars. We compared the performance of nanopillars from two different arrays: one with top diameter of 600 nm and pitch 1500 nm and the second with top diameter of 400 nm and pitch 2500 nm. We showed that the smaller diameter produces a larger field enhancement on the nanopillar top border, while a larger pitch causes a lower electrostatic screening, favouring the extraction of FE current with lower applied field. By analysing the simulations of the electric field, we demonstrated that almost all the current is emitted from an annular area of width 10 nm at the top border of the nanopillar.

References

[1] Murphy E L and Good R H 1956 Thermionic emission, field emission, and the transition region *Phys. Rev.* **102** 1464–73
[2] Gomer R 1961 *Field Emission and Field Ionization* (Cambridge: Harvard University Press)
[3] de Heer W A, Ch telain A and Ugarte D 1995 A carbon nanotube field-emission electron source *Science* **270** 1179–80
[4] Shao X, Srinivasan A, Ang W K and Khursheed A 2018 A high-brightness large-diameter graphene coated point cathode field emission electron source Nat. Commun. 9 1288

[5] Zhang J, Yang G, Cheng Y, Gao B, Qiu Q, Lee Y Z, Lu J F and Zhou O 2005 Stationary scanning x-ray source based on carbon nanotube field emitters Appl. Phys. Lett. 86 184104

[6] Milne W I et al 2006 Aligned carbon nanotubes/fibers for applications in vacuum microwave amplifiers J. Vac. Sci. Technol. B 24 345–8

[7] Di Bartolomeo A, Urban F, Passacantando M, McEvoy N, Peters L, Iemmo L, Luongo G, Romeo F and Giubileo F 2019 A WSe2 vertical field emission transistor Nanoscale 11 1538–48

[8] Di Bartolomeo A, Rücker H, Schley P, Fox A, Lischke S and Na K Y 2009 A single-pole EEPROM cell for embedded memory applications Solid-State Electron. 53 644–8

[9] Chen Z, Zhu F, Wei Y, Jiang K, Liu L and Fan S 2008 Scanning focused laser activation of carbon nanotube cathodes for field emission flat panel displays Nanotechnology 19 135703

[10] Bonard J M, Kind H, Stöckli T and Nilsson L O 2001 Field emission from carbon nanotubes: the first five years Solid-State Electron. 45 893–914

[11] Giubileo F, Di Bartolomeo A, Iemmo L, Luongo G and Urban F 2018 Field emission from carbon nanostructures Applied Sciences 8 526

[12] Giubileo F, Bartolomeo A D, Scarfato A, Iemmo L, Bobba F, Passacantando M, Santucci S and Cucolo A M 2009 Local probing of the field emission stability of vertically aligned multi-walled carbon nanotubes Carbon 47 1074–80

[13] Smith R C, Cox D C and Silva S R P 2005 Electron field emission from a single carbon nanotube: Effects of anode location Appl. Phys. Lett. 87 103112

[14] Di Bartolomeo A, Scarfato A, Giubileo F, Bobba F, Biasiucci M, Cuolo A M, Santucci S and Passacantando M 2007 A local field emission study of partially aligned carbon-nanotubes by atomic force microscope probe Carbon 45 2957–71

[15] Passacantando M, Bussolotti F, Santucci S, Di Bartolomeo A, Giubileo F, Iemmo L and Cuolo A M 2008 Field emission from a selected multiwall carbon nanotube Nanotechnology 19 395701

[16] Giubileo F, Iemmo L, Luongo G, Martucciello N, Raimondo M, Guadagno L, Passacantando M, Lafdi K and Di Bartolomeo A 2017 Transport and field emission properties of buckypapers obtained from aligned carbon nanotubes J. Mater. Sci. 52 6459–68

[17] Giubileo F, Di Bartolomeo A, Sarno M, Altavilla C, Santandrea S, Ciambelli P and Cuolo A M 2012 Field emission properties of as-grown multiwalled carbon nanotube films Carbon 50 163–9

[18] Zeng B, Xiong G, Chen S, Wang W, Wang D Z and Ren Z F 2007 Field emission of silicon nanowires grown on carbon cloth Appl. Phys. Lett. 90 033112

[19] Giubileo F, Di Bartolomeo A, Iemmo L, Luongo G, Passacantando M, Koivusalo E, Hakkarainen T and Guina M 2017 Field Emission from Self-Catalyzed GaAs Nanowires Nanomaterials 7 275

[20] Liu B, Bando Y, Tang C, Xu F, Hu J and Golberg D 2005 Needledike Bicrystalline GaN Nanowires with Excellent Field Emission Properties J. Phys. Chem. B 109 17082–5

[21] Giubileo F, Bartolomeo A D, Zhong Y, Zhao S and Passacantando M 2020 Field emission from AlGaN nanowires with low turn-on field Nanotechnology 31 475702

[22] Yeşilpinar D and Çelebi C 2017 Electron field emission from SiC nanopillars produced by using nanosphere lithography J. Vac. Sci. Technol. B 35 041801

[23] Giubileo F, Passacantando M, Urban F, Grillo A, Iemmo L, Pelella A, Goosney C, LaPierre R and Di Bartolomeo A 2020 Field Emission Characteristics of InSb Patterned Nanowires Adv. Electron. Mater. 6 2000402

[24] Grillo A, Barrat J, Galazka Z, Passacantando M, Giubileo F, Iemmo L, Luongo G, Urban F, Dubourdieu C and Di Bartolomeo A 2019 High field-emission current density from β-Ga2O3 nanopillars Appl. Phys. Lett. 114 193101
[25] Hong X D, Liang D, Wu P Z and Zheng H R 2016 Facile synthesis and enhanced field emission properties of Cu nanoparticles decorated graphene-based emitters Diamond Relat. Mater. 69 61–7

[26] Di Bartolomeo A, Passacantando M, Niu G, Schlykow V, Lupina G, Giubileo F and Schroeder T 2016 Observation of field emission from GeSn nanoparticles epitaxially grown on silicon nanopillar arrays Nanotechnology 27 485707

[27] Iemmo L, Di Bartolomeo A, Giubileo F, Luongo G, Passacantando M, Niu G, Hatami F, Skibitzki O and Schroeder T 2017 Graphene enhanced field emission from InP nanocrystals Nanotechnology 28 495705

[28] Santandrea S, Giubileo F, Grossi V, Santucci S, Passacantando M, Schroeder T, Lupina G and Di Bartolomeo A 2011 Field emission from single and few-layer graphene flakes Appl. Phys. Lett. 98 163109

[29] Kumar S, Duesberg G S, Pratap R and Raghavan S 2014 Graphene field emission devices Appl. Phys. Lett. 105 103107

[30] Di Bartolomeo A, Giubileo F, Iemmo L, Romeo F, Russo S, Unal S, Passacantando M, Grossi V and Cucco A M 2016 Leakage and field emission in side-gate graphene field effect transistors Appl. Phys. Lett. 109 023510

[31] Kashid R V, Late D J, Chou S S, Huang Y-K, De M, Joag D S, More M A and Dravid V P 2013 Enhanced Field-Emission Behavior of Layered MoS2 Sheets Small 9 2730–4

[32] Giubileo F, Grillo A, Passacantando M, Urban F, Iemmo L, Luongo G, Pelella A, Loveridge M, Lozzi L and Di Bartolomeo A 2019 Field Emission Characterization of MoS2 Nanoflowers Nanomaterials 9

[33] Rout C S, Joshi P D, Kashid R V, Joag D S, More M A, Simbeck A J, Washington M, Nayak S K and Late D J 2013 Superior Field Emission Properties of Layered WS2-RGO Nanocomposites Sci. Rep.-UK 3 3282

[34] Giubileo F, Iemmo L, Passacantando M, Urban F, Luongo G, Sun L, Amato G, Enrico E and Di Bartolomeo A 2019 Effect of Electron Irradiation on the Transport and Field Emission Properties of Few-Layer MoS2 Field-Effect Transistors J. Phys. Chem. C 123 1454–61

[35] Di Bartolomeo A, Pelella A, Urban F, Grillo A, Iemmo L, Passacantando M, Liu X and Giubileo F 2020 Field emission in ultrathin PdSe 2 back-gated transistors Adv. Electron. Mater. 6 2000094

[36] Urban F, Passacantando M, Giubileo F, Iemmo L and Di Bartolomeo A 2018 Transport and Field Emission Properties of MoS2 Bilayers Nanomaterials 8 151

[37] Fowler R H and Nordheim L 1928 Electron Emission in Intense Electric Fields P. Roy. Soc. A-Math. Phy. 119 173–81

[38] Forbes R G and Deane J H B 2007 Reformulation of the standard theory of Fowler–Nordheim tunnelling and cold field electron emission P. Roy. Soc. A-Math. Phy. 463 2907–27

[39] Forbes R G 2020 Comment on “Advanced field emission measurement techniques for research on modern cold cathode materials and their applications for transmission-type x-ray sources” Rev. Sci. Instrum. 91 083906

[40] Goosney C J, Jarvis V M, Wilson D P, Goktas N I and LaPierre R R 2019 InSb nanowires for multispectral infrared detection Semicond. Sci. Tech. 34 035023

[41] Cai D and Liu L 2013 The screening effects of carbon nanotube arrays and its field emission optimum density AIP Advances 3 122103

[42] Nilsson L, Groening O, Emmenegger C, Kuettel O, Schaller E, Schlaphach L, Kind H, Bonard J-M and Kern K 2000 Scanning field emission from patterned carbon nanotube films Appl. Phys. Lett. 76 2071–3