Inter*net* Electronic Journal*

Nanociencia et Moletrónica

Junio 2013, Vol.11, N°1, pp 2031-2040

A nanomechatronic sensor for the detection of nanoscale vibrations

A. Ramírez, E. Molina, A. Zehe

Benemérita Universidad Autónoma de Puebla
Facultad de Ciencia de la Electrónica, Laboratorio de Nanotrónica
Ciudad Universitaria, 72550 Puebla, Pue., México
arami@ece.buap.mx

recibido: 16.12.12 revisado: 22.01.13 publicado: 31.07.13

Citation of the article;
A. Ramírez, E. Molino, A nanomechatronic sensor for the detection of nanoscale vibrations,
Int. Electron J. Nanoc. Moletrón, 2013, Vol. 11, N°1, 2031-2040

A nanomechatronic sensor for the detection of nanoscale vibrations

A. Ramírez, E. Molina, A. Zehe

Benemérita Universidad Autónoma de Puebla
Facultad de Ciencia de la Electrónica, Laboratorio de Nanotrónica
Ciudad Universitaria, 72550 Puebla, Pue., México
arami@ece.buap.mx

recibido: 16.12.12 revisado: 22.01.13 publicado: 31.07.13

Internet Electron. J. Nanoc. Moletrón., 2013, Vol.11 , N° 1, pp 2031-2040

ABSTRACT

In ultra-precision machining and ultra-fine materials processing, the dimensional accuracy of manufactured parts is affected by the dynamical behavior of the positioning system, as the presence of vibrations can cause unwanted motion in any axis. Displacement sensors, like piezoelectric, capacitive or inductive sensors are mostly used in those applications, while for oscillation measurements of the vibrating beam in AFM-applications, Single Electron Transistors (SET's) are also applied.

We propose a discrete multi-tip vibration sensor, which is sensitive down to a few nanometers of oscillation amplitude. Cold field electron emission from an array of nano-size cones grown on SiC is applied, where the distance between the tip of emitting mounds and the counter-electrode (anode) is changed in the rhythm of the vibrating object under study.

KEY WORDS: Nano-Mechatronics, vibration sensor, field electron emitter, nanoscale device

1. INTRODUCTION

The characterization of physical phenomena of materials and devices on the nano-scale is one of the important challenges for researchers and engineers since the advances of nanotechnology have led to the emergence of new operation principles. Micro- and Nano Electro Mechanic Systems (MEMS, NEMS) are devices that integrate electrical and mechanical functionality at micro- or nanoscale (Philip Wong et al, 2011).

In ultra-precision machining and ultrafine materials processing, the application of rotation devices with corresponding precision requirements is mandatory (Hinklin et al, 2009; Toro et al, 2010). The dimensional accuracy of manufactured parts is affected by the dynamical behavior of the positioning system, as the appearance of vibrations can cause unwanted motion in any axis. Displacement sensors, like piezoelectric accelerometer sensors, capacitive or inductive distance sensors are mostly used in these applications.
Nanometer scale structures, like the vibrating beam in a Scanning Probe Microscope (AFM, STM) can oscillate at several million times per second. To measure these vibrations, Single Electron Transistors (SET's) are often being used. Device structures of this kind can be applied for force sensors, as radio-frequency circuit elements, or even as objects of study at the quantum/classical boundary themselves.
We propose a vibration sensor, which is sensitive down to a few nanometers of oscillation amplitude. Cold field electron emission from an array of nano-size cones grown on SiC is applied, where the distance between the tip of emitting mounds and the counter-electrode (anode) is controlled by the vibrating object under study. There are recent attempts to develop large-area emitters on flexible substrates, which would allow the internal cathode array to follow external vibrations. Trying to increase the upper frequency response, and improve the readout sensitivity of such nano-mechatronic systems is an important task of present applied research and nano-metrology.

2. ULTRA-PRECISION DEVICES IN MEASURING PROCESSES

Recent promises and achievements in nanotechnology have led to the emergence of new challenges in micro- and nano-mechatronics due to the need of highly sensitive sensors and actuators for the characterization of physical phenomena and operation principles of new devices (Fursey et al, 2011; Schreiner et al, 2011). Rotation devices with ultra-precision requirements are an essential part of actual precision manufacturing procedures, as e.g. milling and drilling, in order to produce components with micro- or nano scale features. Vibrations of the work piece due to imbalance against e.g. the cutting tool affect the final quality of the product.

On the other hand are micro-components known, where their vibration is part of the measuring principle. Without cantilever transducers, atomic force microscopy would not be possible. Such beams are the most universal structures in the field of micro-mechatronic systems. The vibrating beam in a Scanning Probe Microscope (AFM, STM) oscillates at Megahertz frequencies, while with cantilevers on the nano-scale even Gigahertz frequencies are reached. The precise knowledge of these frequency measures are needed in particular applications of such cantilever beams. A wellknown formula relates the spring constant *k*to the dimensions and material properties of the cantilever:

$$k = \frac{F}{\Delta} = \frac{Ewt^3}{4L^3} \qquad (1)$$

where *F* is the acting force, *Δ* is the cantilever end deflection, *E* is Young's modulus, *t* the thickness, *L* the length and *w* is the cantilever's width. The spring constant is related to the cantilever resonance frequency *ω* by the usual harmonic oscillator formula $\omega = (k/m)^{1/2}$. A change in any of the cantilever parameters, particularly by loading an additional mass onto the cantilever beam (Jensen et al, 2008; Krauss, 2009), will affect the resonance frequency, which can be measured with high accuracy by use of heterodyne techniques.

Considering the charge sensitivity of a Single Electron Transistor (SET), the displacement of a cantilever can be detected with high sensitivity from the capacitance variation between the quantum island and the gate formed on the cantilever. Movement of a nanometer-sized beam changes the voltage on the gate electrode, which then changes the current running through the transistor. The detection of cantilever displacements using a sensitive charge perceiving device such as an on-chip quantum point contact (Teufel et al, 2009) has been demonstrated for some years. SET's as motion detectors, capacitively coupled to voltage-biased doubly clamped beams or nano-mechanical resonators, have been applied by several groups who then demonstrated impressive displacement sensitivities (Naik et al, 2006). The point here is, that the SET has to be integrated completely into the vibrating device already during the fabrication process of the measuring unit.

In many applications, a discrete sensor device even in the nanometer range is a desirable choice. Piezoelectric accelerometer sensors, capacitive or inductive sensors are of that type. In the following, we describe a further variant.

3. FIELD ELECTRON EMISSION SENSOR

The electron emission from a metallic or semiconductor surface via quantum mechanical tunneling into vacuum space is commonly referred to as field emission. Field emission from planar metal surfaces was described by Fowler and Nordheim several decades ago (Fowler et al, 1928). It occurs when a sufficiently high electric field of about 10^{10} V/m operates at the location of emission. On the other hand can small-scale features within a low average electric field produce a high local field. Elongated structures such as cathode tip structures provide for a geometric electric field enhancement and substantially improved emission behavior of the cathode. Within the framework of the planar field emission picture, this enhancement is described by multiplying the applied (global) field *F* with a field enhancement factor *γ.* Provided that $\gamma > 1$, the local field at the tip becomes *γF.* The field enhancement factor depends strongly on the small-scale structure of the tip. For such emitters has been shown (Everhart, 1967; Kokkorakis et al, 2011) that *γ* is inversely proportional to the tip radius *r.* Young (1963) and Binnig et al (1983) viewed tips as "a kind of continuous matter with some radius of curvature". At that time, a tip radius of 100 nm was common for the state of the art single field emission tips. Low voltage emission is achieved, when the tip radius is as small as possible. As we have shown in a previous paper (Ramírez et al, 2011), values of *r* as low as a molecular radius of SiC emitter tips can be imagined. Nanoscale tips produce extremely large curvature in the vacuum potential near the emission site. Electrode spacing *L* should be small, too, in order to avoid space charge build up and produce high emission at low applied voltage.

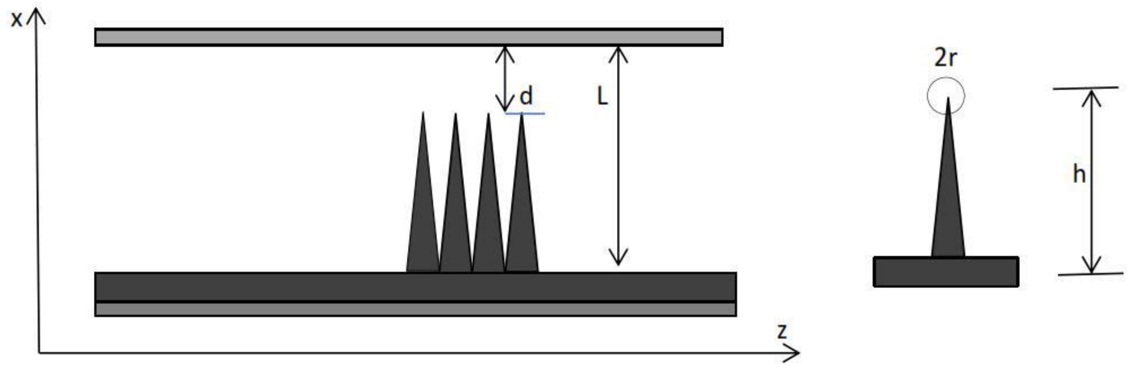

Fig. 1: Cold cathode emitter structure with nanoscale emitter tip (*right*). The cathode-anode distance is *L*, the distance of the emitter tip to the anode is *d*. The height *h* and the tip radius *r* of the cone result in an aspect ratio $\sigma=h/2r$. The applied voltage *U* generates a (global) electric field of about $F=U/L$, given that usually L>>d.

With some minor assumptions outlined by Fisher and Walker (Fisher et al, 2002), the current density can be expressed similar to the basic Fowler-Nordheim relation as

$$J=1.5\cdot 10^{6}\cdot\Phi^{-1}\cdot (\gamma F)^{2}\cdot exp(10.4/\Phi^{1/2})\cdot \exp(-6.44\cdot 10^{7}\cdot\Phi^{3/2}/\gamma F) \qquad (2)$$

where *J* is the average current density (A/cm^2), γ is the field enhancement factor, *F* is the (global) applied electric field (V/cm), and Φ is an effective work function of the emitter material. The required electric field is about F=10^6 V/m for a tip radius of r=5 nm. High electric fields are achieved in the vicinity of conducting objects with small radii of curvature, which locally enhance the external electric field *F*.

Using the notation given in Fig. 1, a useful equation for γ is

$$\gamma = 1.2\,(3.15 + h/r)^{0.9} \qquad (3)$$

although more involved approaches are known, too (see Podenok et al. 2006).
Typical values for the current emission of a single tip are observed at about 10^{-7} A. Provided that the self-organization of tips during the growth process generates tip densities of 10^4 tips/μm^2, the integral current emission of such an arrangement may deliver values up to 1 mA.

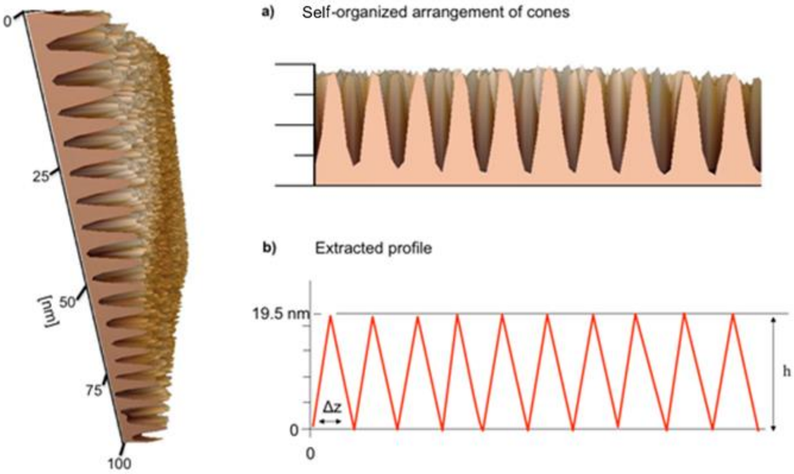

Fig. 2: Dense array of cones grown on a SiC substrate (a). The extracted profile (b) shows the base diameter and cone height. The radius of each tip may be no larger than half a molecule diameter of SiC, providing for a aspect ratio of σ=39.

In Fig. 2 an AFM image of an array of SiC cones grown on a SiC substrate is shown. The number of cones being about 10^{12} tips/cm^2 turns out to be extremely high. The size of each cone with base diameter of 5.4 nm and height of 19.5 nm suggests quantum dot behavior with at least one discrete energy level E_0. Further provides the geometrical closeness between cones, that the discrete energy levels E_0 merge into a miniband, as shown in Fig. 3. A strong field electron emission can thus be expected.

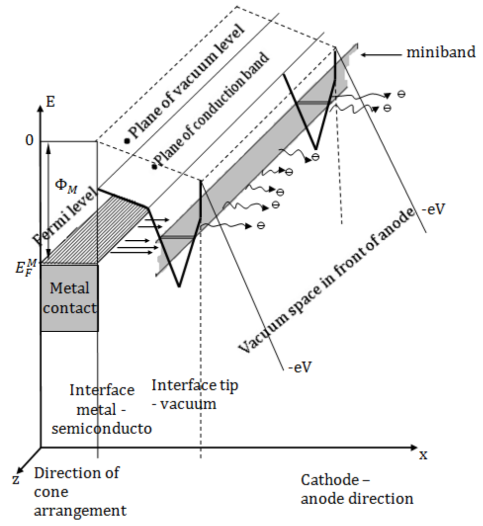

Fig. 3: Energy band structure of the quantum dot array after Fig. 2.

Consider now a device shown in Fig. 4, where the distance *d* between the emitting point source and the base cathode is allowed to oscillate by $\pm\delta d$.

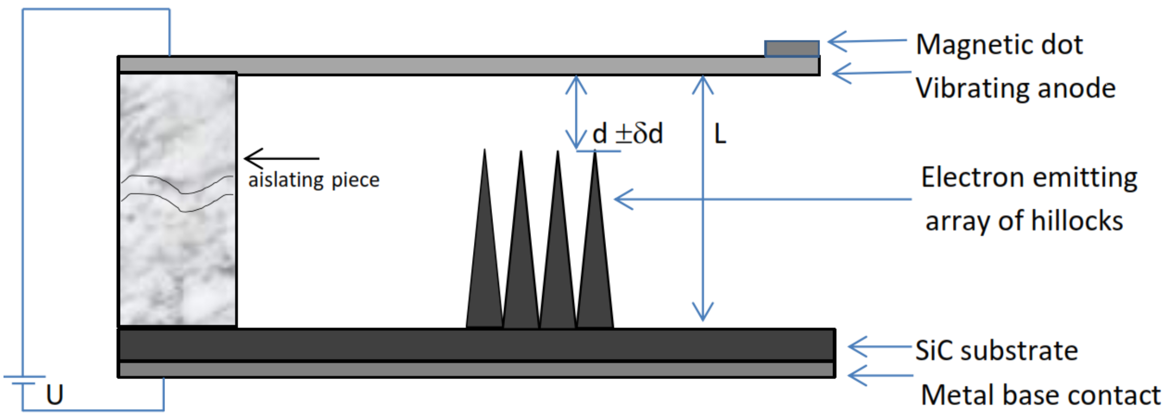

Fig. 4: Cold cathode emitter device, where the distance *d* between the tip of the emitter and the anode is allowed to oscillate by $\pm\delta d$. This may be achieved by a flexible substrate or a magnetically displaced anode.

Let us choose an electrode distance of 1 μm, and apply a voltage of U=10 V, then a field value above the required applied field of 10^7 V/m is generated. Now consider variations of δF due to an oscillation of the anode-cathode distance by δd (see Fig. 4). With only a variation $\delta d=\pm 5$ nm, the local field experiences a variation of $\delta F=\pm\ 10^3$ V/m or 10^{-2} % of its working value. Such variation of *F* translates into a variation of the electron emission density. The relative variation of the current density after eq. (2) is proportional to the variation of the local electric field,

$$\delta J/J = (2/F - B/F^2)\ \delta F \qquad (4)$$

where *B* combines material and geometry parameters contained in the latter exponential function of equ. (2). In a first approximation we get for $\delta J = 2\ 10^{-11}$ *A* per tip, but considering the mentioned tip density of the arrangement, this value growths up to $\delta J = 2\ 10^{-7}$ A. This is a remarkable value for the measuring signal of the moving system.

SUMMARY AND CONCLUSIONS

Field emission devices may offer an intriguing new technical approach for compact fast vibration sensors. To that end, field emission electron sources are built on a flexible substrate, which can take on and transfer the oscillations of a vibrating moving system into a change of the spacing distance between cathode and anode, and by this modulate the emission current density. If build on a rigid substrate, the anode could be shifted, e.g., by means of a magnetic field coupled to the vibrating moving system. Given the nanoscale properties of such a device, both high electrical sensitivity and mechanical response can be expected. Many technical challenges remain, though, particularly as flexible substrates, and the self-organization of tiny electron emitter cones in an array with high tip density are still a matter of research. A further major challenge lies in the demonstration of a practical engineering set up, which has not yet reached.

ACKNOWLEDGMENTS

The authors thank SEP/CONACyT de México, and the authorities of the Autonomous University of Puebla (BUAP) for financial support. Technical support of M.C. Ramiro Gomez, Ernesto González Hernández and Rodolfo Arturo Hernández Reyes is kindly acknowledged.

REFERENCES

Binnig, G., Rohrer, H., Gerber, Ch., Weibel, E. (1983) "7 x 7 reconstruction on Si(111) resolved in real space" Phys. Rev. Lett. 50, 120-123

Everhart, T.E. (1967) "Simplified analysis of point-cathode electron sources", J. Appl. Phys. Vol. 38, pp 4944-57

Fisher, T.S., Walker, D.G. (2002) "Thermal and electrical energy transport and conversion in nanoscaleelectron field emission processes", Transact. ASM, Vol. 124, pp 954- 962

Fowler, R.H., Nordheim, L.W. (1928) "Field emission from metallic surfaces", Proc. R. Soc. London,Ser.Avol. 119, pp 173-181

Fursey, G.N., Polyakov, M.A., Yafyasov, A.M. Bogevolnov, V.B. (2011) "Exceptionally low thresholdof field emission from carbon nanostructures", Proc. Int. Vacuum Nanoelectronics Conf.Regensburg, 2011

Hinklin, T. & Lu, K. (2009)"Role of Lattice Vibrations in a Nanoscale Electronic Device", in *Processing of Nanoparticle Structures and Composites* (eds T. Hinklin and K. Lu), JohnWiley & Sons, Inc. Hoboken, NJ, USA.doi:10.1002/9780470551532.ch7

Jensen, K. Kim, K., Zettl, A.(2008) "An atomic resolution nanomechanical mass sensor", Nat. Nanotechnol. Vol. 3, pp.533-37

Kokkorakis, G.C., Kyritsakis, A., Xanthakis, J.P. (2011) "Enhancement factor γ of a sharp emitting tip: a revisit with the aim of a simple formula for γ", Proc. Int. Vacuum Nanoelectronics Conf.,Regensburg, 2011

Krauss, T.D. (2009) "Biosensors: Nanotubes light up cells", Nat. Nanotechnol. 4, pp 85-86

Naik, A., Buu, O., LaHaye, M.D., Blencowe, M.P.,Armour, A.D., Clerk, A. A., K.C. Philip Wong, H.S., Deji Akinwande (2011) "*Carbon nanotube and graphenedevice physics*", Cambridge University Press, Cambridge, N.Y.,Mexico City, 2011

Podenok, S., Sveningsson, M., Hansen, K., Campbell, E.E.B. (2006), NANO: Brief Reports and Reviews, Vol. 1, N°1, 87-93

Ramírez Solís, A., Gómez Puerto, R., A. Zehe (2011) “Emisión por Campo de Electrones desde ArreglosNanométricos”, *Internet Electron J. Nanoc. Moletrón*, Vol. 9, N°2, pp 1701-1714

Schreiner, R., Dams, F., C. Prommesberger, C., Bornmann, B., Serbun, P., Navitski, A., Müller, G (2011), “Silicon-based integrated field emission electron sources for sensor application”, Proc. Int. Vac. Nanoelectronics Conf. Regensburg, pp 19-20

Schwab. (2006) "Quantum Measurement Backaction and Cooling Observed with a Nanomechanical Resonator", *Nature* vol. 443, pp. 193-196

Teufel, J.D., Donner, T. Castellanos-Beltran, M. A., Harlow, J. W. & K. W. Lehnert (2009)“Nanomechanical motion measured with an imprecision below that at the standard quantum limit”, *Nature Nanotechnology,* **vol. 4**, pp. 820 - 823

Toro, R. M., Haber, R. E., Schmittdiel, M. (2010). “Detecting Nano-Scale Vibrations in RotatingDevices by using Advanced Computational Methods”,*Sensors*, Vol. 10, pp. 4983-4995.doi:10.3390/s100504983

Young, R.D. (1963) “Field Emission Ultramicrometer”, Rev. Sci. Instr. 37, 275-278