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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

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Abstract
A new discrete vibration sensor is proposed, 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 hillocks and the counter-electrode (anode) is changed in the rhythm of the vibrating object under study.

Key words: Field electron emitter, nanoscale device, vibration sensor, ultraprecision machining, Silicon Carbide

Resumen
Proponemos un nuevo sensor discreto de vibración, que es sensitivo hasta unos pocos nanómetros del amplitud de oscilación. Emisión de campo eléctrico en frío desde un arreglo de conos de tamaño nanométrico crecido sobre SiC es aplicada, donde la distancia entre la punta de los montículos emisivos y el contra-electrodo (ánodo) se cambia en el ritmo de las vibraciones del objeto estudiado.

Palabras clave: Emisor de electrons por campo, dispositivo a nanoescala, sensor de vibración, fabricación ultra-precisa, Carburo de Silicio

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 electronical and mechanical functionality at micro- or nanoscale dimensions [1].

In ultra-precision machining and ultrafine materials processing, the application of rotation devices with corresponding precision requirements is mandatory [2, 3]. 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 be 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 new 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 [4], 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 nanometrology.

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 [5,6]. 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 micromechatronic 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 well-known formula relates the spring constant *k* to the dimensions and material properties of the cantilever:

$$k = F/\Delta = Ewt^3/4L^3 \quad (1)$$

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 $\omega = (k/m)^{½}$. A change in any of the cantilever parameters, particularly by loading an additional mass onto the cantilever beam [7,8], 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 [9] has been demonstrated for some years. SET's as motion detectors, that are capacitively coupled to voltage-biased, doubly clamped beams or nanomechanical resonators, have been applied by several groups who then demonstrated impressive displacement sensitivities [10]. 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 [11]. 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 [12, 13] that *γ* is inversely proportional to the tip radius *r.* Thus, low voltage emission is achieved, when the tip radius is as small as possible. As we have shown in a previous paper [14], 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.

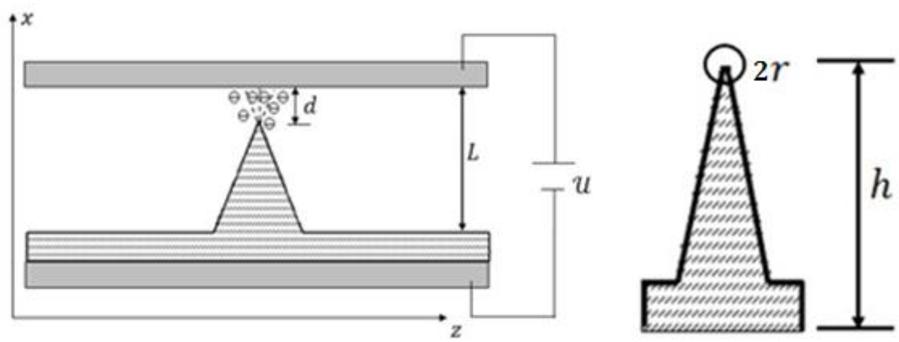

Fig. 1: Cold cathode emitter structure with nanoscale emitter tip (der.). The cathode-anode distance is *L*, the distance of the emitter tip to the anode is *d*. The hight *h* and the tip radius *r* of the cone result in an aspect ratio $\sigma=h/2r$. The applied voltage *U* generates a (global) electric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

With some minor assumptions outlined by Fisher and Walker [15], the current density can be expressed similar to the basic Fowler-Nordheim relation as

$$J=1.5\cdot10^{6} \cdot \Phi^{-1}\cdot (\gamma F)^{2} \cdot exp(10.4/\Phi^{1/2}) \cdot \exp(-6.44 \cdot 10^{7}\cdot\Phi^{3/2}/\gamma F) \qquad (2)$$

where *J* is the average current density (A/cm^2), *F* is the (global) applied electric field (V/cm), and Φ is an effective work function of the emitter material (eV). The required electric field is about F=10^6 V/m for a tip radius of r=5 nm.

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.

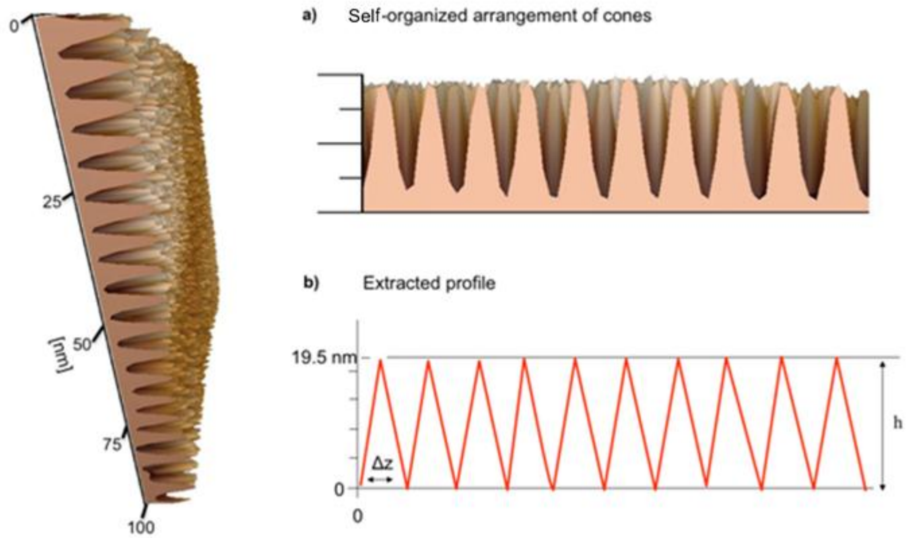

Fig. 2: Dense array of cones grown on a SiC substrate (a). The extracted profile (b) shows the base diameter and cone height. The radius of each tip may be no larger than half a molecule diameter of SiC, providing for a aspect ratio of σ=39.

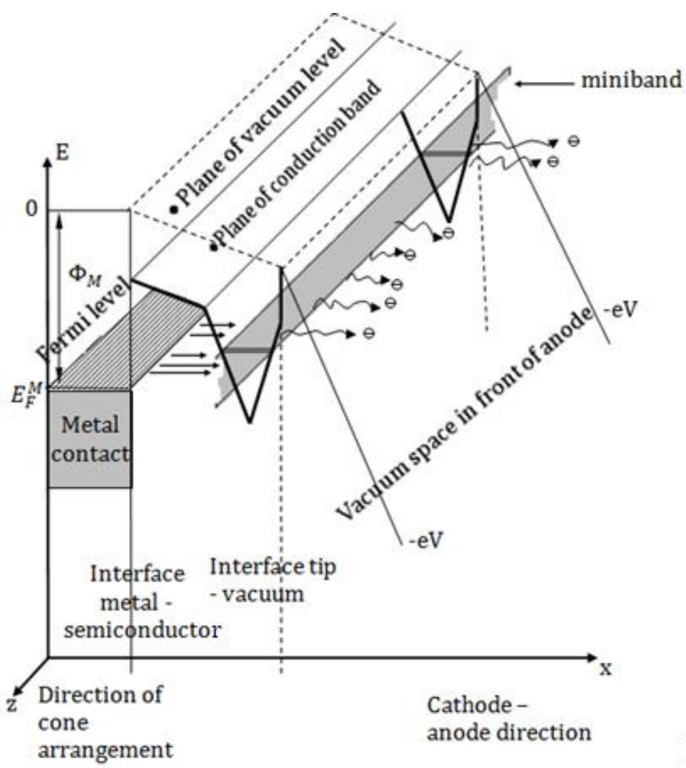

Fig. 3: Energy band structure of the a quantum dot array after Fig. 2.

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 $\pm\delta d$.

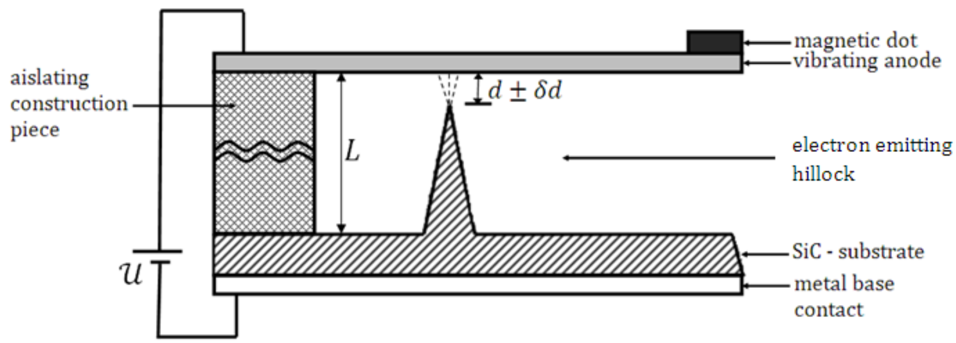

Fig. 4: Cold cathode emitter device, where the distance *d* between the tip of the emitter and the anode is allowed to oscillate by $\pm\delta d$. This may be achieved by a flexible substrate or a magnetically displaced anode.

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 corresponding to eq. (2), and delivers 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.

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