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Nanoscale oscillation verification based on a field electron emitting quantum-dot array

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ABSTRACT

Scientific and technological progress of the last decade has proven that quantum-dot arrays have received tremendous attention for the next generation of nano- and optoelectronic devices. An electronic displacement device by positioning a vibrating anode toward a special field electron emitter is presented. Cold field electron emission from an array of quantum dots grown on silicon carbide is applied, where the distance between the tip of emitting cones and the counter-electrode (anode) is controlled by the vibrating object under study. Concluding from Fowler-Nordheim equations, sensitivity down to a few nanometers of the vibration amplitude is possible.

1. Introduction

The description of physical phenomena of materials and devices on the nanoscale has become one of the important challenges for researchers since the advancement of nanotechnology has led to the emergence of new operation principles [1–3]. Scientific and technological progress of the last decade has proven that quantum-dot (QD) arrays have received tremendous attention for the next generation of nano- and optoelectronic devices like QD lasers, QD memories, etc. Quantum dots are potentially ideal for their integration with optical devices and detectors. Considerable progress has been achieved in fundamental investigations of quantum computing and quantum communications [4–7]. Quantum-dot cellular automata (QCA) technology uses quantum dots instead of transistors and diodes for performing the logical operations for computing at nanoscale by monitoring the position of a single electron [1,5–7]. Experimental and theoretical works along these lines have revealed novel physical phenomena like the nonlinear optical response of semiconductor quantum dot structures, self-focusing effects, the Kerr effect, and solitary waves in an array of quantum dots [8–11].

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 themselves can even be applied as objects of study at the quantum/classical boundary.

In this work, we study the viability of a displacement sensor for nanoscale vibration, which is sensitive down to a few nanometers of oscillation amplitude. Cold field electron emission from an array of nanosize cones grown on SiC is applied, where the distance between the tip of emitting mounds and the counter-electrode (anode) is controlled by the moving object under study. 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 explore a further option.

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2. Cold cathode emitter structure

The electron emission from a metallic or semiconductor surface via quantum mechanical tunneling into the vacuum space is commonly referred to as field emission. Fowler and Nordheim described field emission from planar metal surfaces several decades ago. It occurs when a sufficiently high electric field of about 10 GV/m operates at the location of emission [12]. On the other hand, small-scale features within a low average electric field can produce a high local electric field. Elongated structures such as cathode tip structures provide for a geometric electric field enhancement and substantially improved emission behavior of the cathode [13–15]. In the cited works, the authors derived analytically from first principles a generalized Fowler–Nordheim type equation that takes into account the curvature of a nanoscopic emitter and is generally applicable to any emitter shape provided that the emitter is a good conductor and no field-dependent changes in emitter geometry occur. The traditional Fowler–Nordheim equation is shown to be a limiting case of the equation obtained in the limit of emitters of large radii of curvature *R*. Experimental confirmation of the validity of the generalized equation was given by the authors using three different examples.

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 that γ is inversely proportional to the tip radius ***r***. Low voltage emission is achieved, when the tip radius is as small as possible. It has been shown in Ref. [16] that the 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.

In order to prove the effectiveness of the proposed structure, not so much for absolute values of the cold cathode emission, but to observe their changes, it is sufficient for practical purposes to use a simplified standard Fowler-Nordheim-type equation. With some minor assumptions, the current density can be expressed similar to the basic Fowler-Nordheim relation as

$$J = \lambda_M \frac{a}{\Phi}(\gamma F)^2 \exp\left[-\frac{v(f)b\Phi^{3/2}}{\gamma F}\right], \tag{1}$$

where $a = 1.541434 \times 10^{-6}$ (A × eV/V^2) is the first Fowler-Nordheim constant, $b = 6.830890$ (eV$^{-3/2}$ V nm^{-1}) is the second Fowler-Nordheim constant, *J* is a macroscopic emission current density (A/nm^2), γ is the macroscopic field enhancement factor, $F = U/d$ is the macroscopic field generated by the voltage *U* across metallic contacts of distance *d, F* is the local thermodynamic work function of the emitter material, and λ_M is a macroscopic pre-exponential correction factor.

The applied voltage (V/nm) determines the value of *F* and the principal Schottky-Nordheim barrier function

$$v(f) = 1 - f + f\ln(f) \tag{2}$$

depends on the scaled barrier field $f = (1.439964\,\text{eV}^2\,\text{V}^{-1}\,\text{nm}) \times \gamma F/\Phi^2$.

Although Eq. (1) might be defective and overestimates current densities, to the end of the present discussion, it should not disturb the conclusions. Eq. (1) is widely used to partially fit field emission data, with parameter γ, which can be interpreted simply as a field enhancement factor, as a fitting parameter. The correction factor λ_M is highly variable between field effect emitters and difficult to determine reliably, but usually lies between 10^{-11} and 10^{-5} [15]. Such a new Fowler-Nordheim-type equation responds to advances in field-emitting nanoarrays. The Fowler-Nordheim factors *a* and *b* surge from normal universal constants.

In general, the required electric field depends strongly on the geometry of the emitters. For a special design with thin-film nanotubes (see, e.g. Ref. [17]), the turn-on electric field (as required for achieving an emission current of 10 μA/cm^2) was lowered down to 0.3 V/μm. For a stable field emission performance of a cathode structure as shown in Fig. 1, where the tip radius is about $r = 5$ nm, field intensities of about 0.5 V/nm seem reasonable. High electric fields are generated near conducting objects with small radii of curvature. Using the notation given in Fig. 1, a useful approximate equation is $\gamma = 1.2\,(3.15 + h/r)^{0.9}$.

Values for the electron emission of a single tip under optimum conditions are observed at about 10 nA. Provided that the self-organization of quantum dots during the growth process generates tip densities of 10^4 tips/μm^2 and more, the integral current emission of such an arrangement may deliver values up to 0.1 mA/μm^2.

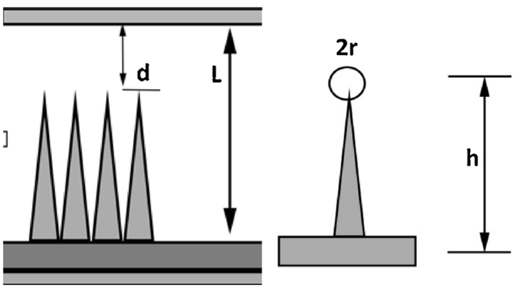

Fig. 1. Cold cathode emitter structure with nanoscale emitter tip (*right*). The cathode-anode distance is *L*, the distance of the emitter tip to the anode is *d*. The height *h* and the tip radius *r* of the cone result in an aspect ratio $\sigma = h/2r$. The applied voltage *U* generates a (global)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