QUANTUM TUNNELING SENSORS

QUANTUM TUNNELING BETWEEN LARGE ARRAYS OF NANOWIRES – NEW SENSING PRINCIPLE, APPLICATIONS IN DEFENSE AND SECURITY AND DEMONSTRATION OF nanoTrek® FUNCTIONALITY

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ABSTRACT

Realisation of the first working sensor based on quantum tunneling between arrays of nanowires[1,2,3] is presented. The sensing element consists of 12,000 nanowires, each 90 nm wide and 5 mm long (~1:55,000 aspect ratio), on an area
of 5 x 4.3 mm. The sensing element was fabricated using phase shift mask lithography and dry etch processes followed by CMP. Characterisation was carried with SEM and AFM.

The first devices we built were configured as linear encoders of position and motion. The devices performance was demonstrated with electrical testing using an independent nanopositioner. Strong signals in μA range were obtained on scans from several hundred nm to several mm range.

The principle of operation can be utilized for trunsduction of dynamic quantities such as vibration, acceleration, pressure, flow and others when timer mechanism is inbuilt or harmonic analysis of signal is implemented. Dynamic quantum tunneling nanoTrek® devices depending on final configuration may be designed and built to function as:

- wireless networks smart sensors for motion detection and perimeter security;
- sonobuoys for Navy;
- vibration sensors in perimeter security sensing, ship building, air-foil testing, building stability;
- accelerometers and gyroscopes for inertial guidance systems, missile guidance, aviation, shipping and automotive;
- image stabilization systems in optical devices in infra-red, night vision, vehicle mounted, cameras and video;
- ultra sensitive microphones for intelligence, medicine or mobile phones;
- displacement and tremor sensors in nuclear test monitoring, mining, mineral exploration, geology, tectonics; or
- seismometers for early earthquake warning systems or tsunami detection.

nanoTrek® APPLICATION IN POSITIONAL METROLOGY: Motivation

Sub-nanometer dimensional metrology plays essential role in advancing microelectronic manufacturing below the 100 nm critical dimensions limit, and then on to the next nodes defined by Sematech International: 65 nm and 45 nm. Metrology tools to reach those next nodes are not well developed. New sub-nanometer metrology solutions and new technology is required [3]. Quantum-π proprietary technology [2] is well suited to offer solutions and to provide the necessary metrology tools. Nanometer and sub-nanometer scale positional metrology is also critical to advancements in nanotechnology, in general. nanoTrek® may address problems of dimensional metrology and alignment at the next technology nodes in micro-fabrication, nano-positioning and nano-imprinting.

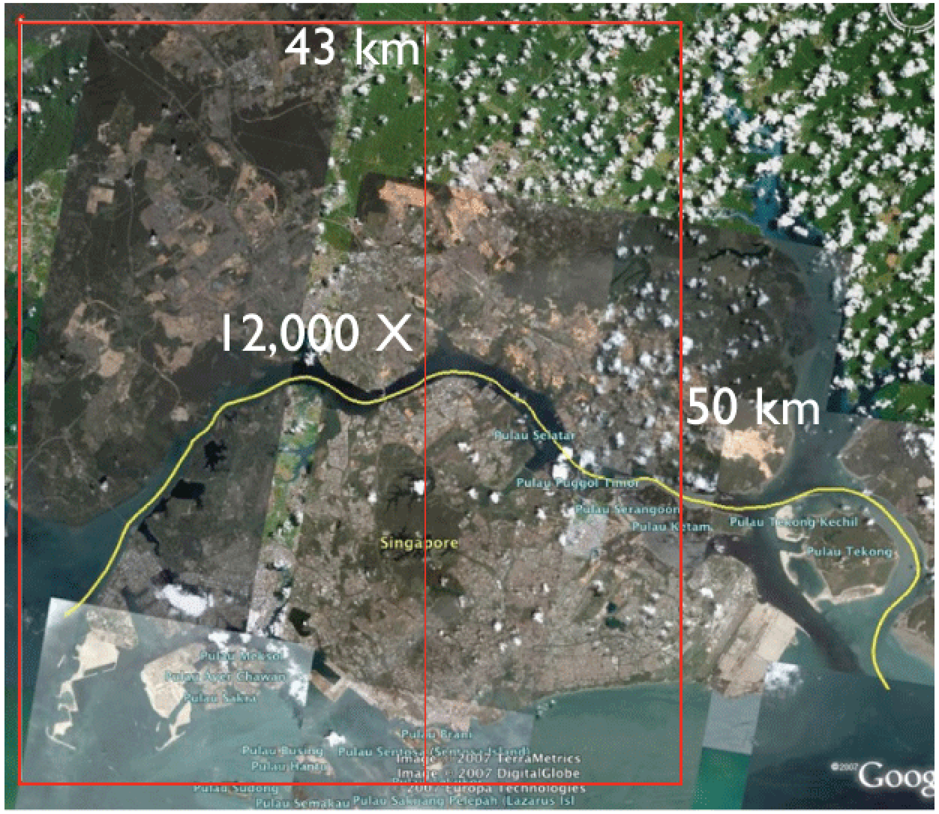

Figure 1: Scale analogy for nanoTrek® devices.

We have demonstrated the first operational linear position encoder based on quantum tunneling between arrays of nanowires. The sensing element consists of 12,000 nanowires, each 90 nm wide and 5 mm long, on an area of 5 x 4.3 mm.

In order to illustrate the scale analogy of nanosystems Quantum-π develops imagine a rectangular plot of land, 31 by
26 miles on each side (Figure 1); absolutely flat, so flat and even, that there is no vertical protrusion, no bump larger than 2 cm on the entire area. Now imagine a straight path 1 meter wide running the entire length of 31 miles, and another one, separated by 2.7 meter, and another one… Imagine 12,000 such 1 meter wide and 31 miles long paths! Now, shrink this picture ten million times and you get an image of nanoTrek® devices. The plot of land is a chip of silicon wafer, the paths are metallic nanowires which are about one thousendth of a width of a human hair (Figure 6)

PRINCIPLE OF OPERATION

Quantum-π technology utilizes physical phenomenon of electron tunneling. Quantum electron tunneling occurs when two electrical conductors are placed in a very close proximity to each other and are separated by an insulating layer. When small bias potential is applied between conductors, electric current flows between them despite no apparent "presence or availablity" of electric carriers in the gap region. Quantum tunneling is an exceedingly sensitive probe of inter-electrode separation, electrode area, the type of electrode material and the nature of intervening insulator. Quantum-π technology is based on variable overlap area of the electrodes.
A generic Quantum-π nanoTrek® device is composed of two plates separated by a very thin layer of soft-matter spacer insulator. Several hundred to several thousand nanowires are fabricated on each substrate. The nanowires on the two surfaces facing each other and aligned with each other form elongated electrodes in the tunneling process. Substrates are allowed to slide past each other while their normal separation remains constant – this makes our device distinctly different from any previously built tunneling sensors where cantilevers and tips were critical elements and it was variable inter-electrode separation that produced transduction signal. Any lateral shift of substrates with nanowires will induce change in alignment and that in turn will result in measurable changes of electrical current flowing between the plates. This effect is demonstrated on Figures 2 and 3 (next page).

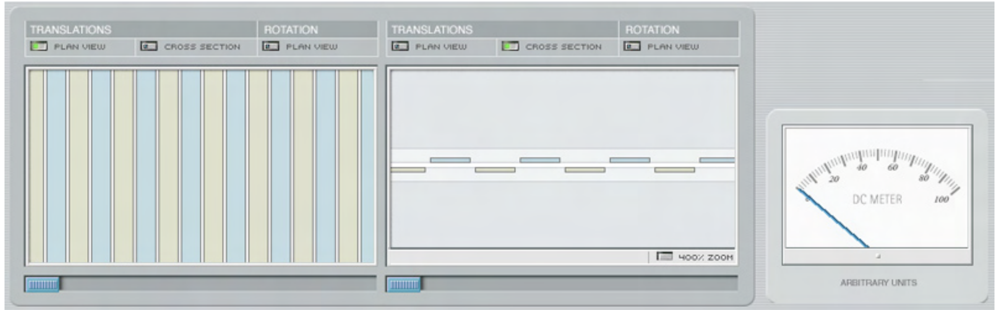

Figure 2: Idealised device showing strips of conductors in off-set position (top projection at left panel, cross section at middle panel, results in no current – right panel).

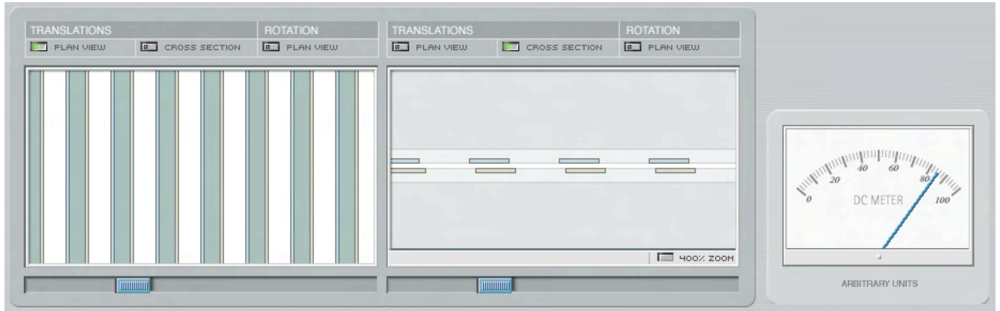

Figure 3: Idealised device showing strips of conductors overlapping each other (top projection at left panel, cross section at middle panel, max current – right panel).

FABRICATION

The sensing element was fabricated using phase shift mask lithography and dry etch processes followed by CMP. Characterisation was carried with SEM and AFM. Finally transduction mechanism, showing linear encoder performance was demonstrated with electrical testing using independent nanopositioner. Strong signals in µA range are obtained on scans from several hundred nm to several mm range.

The fabrication of the presented nanoTrek is done at Institute of Microelectronics, Singapore using 8” Semiconductor processing line. Tantalum Nitride is used as the metal of choice, since it is less prone for native oxide growth. The
sub-100 nm lines at 360 nm pitch were patterned using KrF Nikon lithography scanner with alternating phase shift mask. Dry etching was used to transfer the resist patterns into the metal layer which was followed by USG deposition and CMP for planarization.

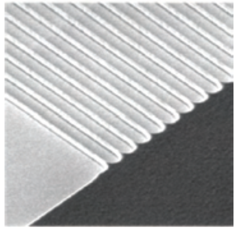

Figure 4: Tilt view SEM image of TaN metal lines – nanowires – before planarization.

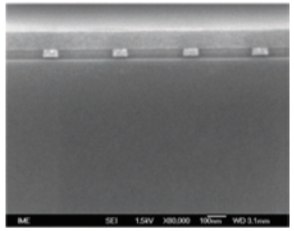

Figure 5: X-section SEM image of TaN nanowires. Width of nanowires is nominally 90 nm. Pitch is 360 nm.

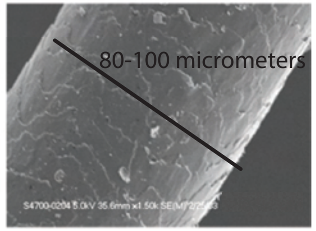

Figure 6: X-section SEM image of human hair – this is ~1000 times wider than a single nanoTrek nanowirewire!

a.

SEM characterisation

The fabricated nanoTrek were physically characterized using X-section SEM and AFM. The SEM image in Fig. 5 clearly shows the well defined nanowires imbedded in dielectric layers.

b. AFM characterisation

Topography imaging of the sample was performed in air using a commercial AFM (Molecular Imaging Corp.) in contact mode using a silicon nitride cantilever (K=0.36 N/m). The left image shows the topography of the sample while the right image shows the friction signal.

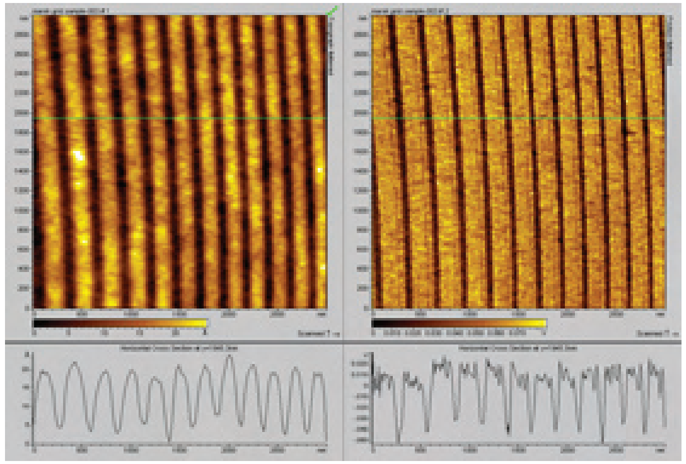

Figure 7.The AFM scans confirm SEM characterisation: well defined nanowires of width 90 nm are separated by 270 nm wide strips of insulator. The conducting nanowires are slightly below insulating strips surface, with 15 nm maximum variation in height. This experiment can in itself be considered almost a “realisation” of the Canon Patent “Encoder using the tunnel current effect” [4]

ELECTRICAL CHARACTERISATION

The electrical testing was performed in cleanroom Class 1,000 environment at Institute of Materials Research and Engineering, Singapore by Quantum-π.

Test setup consists of a mechanical die holder, a nanopositioner (Nanomotion x-y stage PLS 4-30-0.02), which facilitates movement, Keithley 2400 SourceMeter supplying bias voltage, and for measuring the tunnel current, and a computer to run control software.

Samll DC bias voltage is applied to the chips, causing tunnel current flow. For each sample we first measure I-V characteristic, to confirm that the observed current is not Ohmic. In each case studied we observed highly non-linear, typical of tunneling I-V characteristic. We applied reverse bias and varied Voltage between –3 to 3 Volts. In several runs we applied up to 20V potential. The dies are separated by a commercial organic nanolubricant. We expect it to exert some influence when we reverse bias. While one of the dies is stationary, the other is moved in lateral direction so the mutual normal separation between the chips is kept constant, but the plates move laterally in the direction essentially perpendicular to the nanowires.

RESULTS

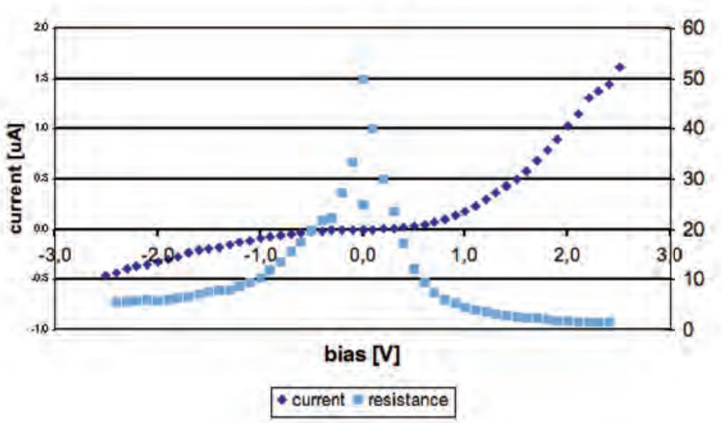

Figure 8. I-V characteristic of nanoTrek.

a. I-V characteristics

Figure 8 illustrates typical I-V characteristic of stationary nanoTrek. Please note that the curve is strongly non-linear, which is consistent with theoretical characteristics of tunneling current.

b. I(x) characteristics

Linear encoder function of the nanoTrek is clearly visible on Figure 9. As the plates move in small steps (40nm in this example) the current varies strongly. Note that nanoTrek is digital-analog encoder in a sense, that the peak-to-peak separation (digital signal) is defined by the physical pitch of the device, but the signal can also be resolved along the slopes of peaks – and hence, in principle, with appropriate signal analysis it can have sub-nanometer (analog) resolution. (Of course, by analogy to quadrature noncontact optical or magnetic encoders, quad, binary or Gray code tunneling encoders can be realised.) With software interpolation we can in principle obtain metrological devices with 0.1 picometer resolution.

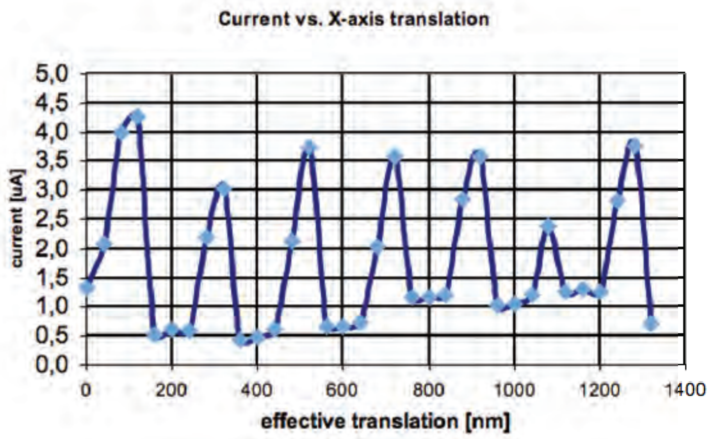

Figure 9. I(x) characteristic.

Uneven height of current peaks is attributed to stick-slip effect due to imperfections of mechanical setup. There is also an effect of quantization as the movement is discrete, not continuous. We are studying these effects, and the ways to avoid them in the next generation of the devices. We have run computer simulations for signal produced from two overlapping grids of 12,000 lines with geometry such as our fabricated samples.

FUTURE – WHAT'S NEXT?

We have demonstrated fabrication processes, a physical embodiment and a proof-of-concept of a tunneling linear encoder. We are continuing performance testing, new fabrication methods, and variety of different applications for our generic nanotrek devices in Singapore and elsewhere. With microfabrication technology available, e.g nanoimprint lithography, we can fabricate nanowires of sever nanometers width and several millimeters long on sensing areas of centimeters. This will allow construction of tunneling linear encoders with sub-nanometer resolutin and centimeter range – a metrology devices for the next microfabrication nodes.

If we add a hardware timer to this device or perform harmonic analysis of time series, we can create NEMS-type dynamic devices (without MEMS fabbing – as our process is planar and requires only few masks) and that will give raise to entre family of motion sensors : sensors that measure changes of motion in time (velocity) and changes of velocity in time (acceleration) and all derived physical quantities, e.g flow meters, microphones, vibration sensors, accelerometers, gyroscopes, pressure meters and many others. Dynamic quantum tunneling nanoTrek® devices depending on final configuration may be designed and built to function as:

- wireless networks of smart sensors for motion detection and perimeter security;
- sonobuoys for Navy;
- vibration sensors in perimeter security sensing, ship building, air-foil testing, building stability;
- accelerometers and gyroscopes for inertial guidance systems, missile guidance, aviation, shipping and automotive;
- image stabilization systems in optical devices in infra-red, night vision, vehicle mounted, cameras and video;
- ultra sensitive microphones for intelligence, medicine or mobile phones;
- displacement and tremor sensors in nuclear test monitoring, mining, mineral exploration, geology, tectonics; or
- seismometers for early earthquake warning systems or tsunami detection.

Our metrology devices and motion sensors are being currently tested by several corporations at their facilities.

REFERENCES

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[3] M. T. Michalewicz et al., "nanoTrek® - Quantum Tunneling Linear Encoder for Sub-nanometer Positional Metrology with Centimeters Range", NSTI Nanotechnology 2007, Santa Clara

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