La agencia de investigación y tecnología de OTAN (RTA) promueve la cooperación e intercambio de información entre los países miembros de la OTAN. Es punto de encuentro de varios centros de investigación de Europa y Norteamérica, donde se identifican áreas de interés, y se proponen proyectos de investigación. Estos proyectos, no se circunscriben al ámbito de defensa, sino que deben ser difundidos para buscar la colaboración y el intercambio de información entre centros y grupos de investigación.

En Diciembre de 2005 tuvo lugar una reunión dentro del panel de Tecnología para Sensores y Electrónica (SET) con el objetivo de identificar intereses comunes en el desarrollo de nanotecnología y nanoelectrónica en el ámbito de los sensores. En siguientes reuniones, se propusieron varios proyectos a desarrollar en colaboración con las instituciones presentes, con el fin de crear un grupo de trabajo OTAN dentro del panel.

Entre los centros representados, se encuentran los siguientes:

- AFRL (Estados Unidos)
- DSTL (Reino Unido)
- Qinetiq (Reino Unido)
- FFI (Noruega)
- DRDC (Canadá)
- Selex (Italia)
- EADS (Francia)
- Universidad de Bilkent (Turquía)
- INTA (España)
- CIDA (España)

Los proyectos propuestos para desarrollar por el grupo de trabajo son tres:

- Nanotubos de Carbono (bulk) para detección de IR
- Nanotubos de Carbono (individuales) para detección de THz, y con énfasis en detección Química y Biológica
- Detectores y Fuentes de *single photon*, basados en estructuras *SAW*

La duración del grupo de trabajo está estimada en 3 años, durante los cuales se espera alcanzar los objetivos propuestos:

- Informe sobre las posibilidades de matrices de nanotubos de carbono como detectores de IR
- Informe sobre las posibilidades de nanotubos de carbono individuales para aplicaciones de sensores.
- Informe sobre fuentes de single photon en el rango 3-5 μm
- Informe sobre las posibilidades de detección de fotones usando estructuras SAW.

Aquellos grupos o centros con interés en trabajar o intercambiar información en alguno de los proyectos, pueden ponerse en contacto con

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Información acerca de los proyectos sigue a continuación.

Carbon nanotube infrared (IR) detectors
Project leader: Canada

Carbon nanotubes (CNT) are used in different areas such as nano-electronics, field emission, composites, fuel cells, chemical and optical detectors. In the last category the properties of CNTs make them interesting candidates in creating a new family of IR detectors. Indeed, this material is known to be a semiconductor with a direct band-gap ranging from 0.1 to 1.0 eV depending on the diameter and chirality (structure) of the CNTs and on its nature (single or multi-wall nanotube). This leads to cut-off wavelengths of 1.2 to 12.0 μm, covering the NIR to LWIR spectrum. In addition, the thermal properties of CNTs imply possible low thermal noise, consequently providing a very good signal to noise (S/N) ratio.

One major unknown factor in using CNTs for IR detection was its sensitivity. In order to achieve satisfactory IR imaging, the quantum efficiency of the semiconductor used as the active material must be sufficient. Recently, a group at IBM research division measured the photoconductivity of a single semi-conducting CNT. The CNT was positioned flat on the substrate between two titanium electrical contacts. A tunable laser was used to illuminate the device and the quantum efficiency of this material was evaluated by measuring the induced photocurrent. The researchers concluded that the quantum efficiency of CNTs was between 10-30% for a single CNT device. This value is lower than the quantum efficiency of HgCdTe but could be brought well above that of quantum well IR photo-detectors (QWIPs) (around 10%). From these results, it is expected that IR detectors based on CNTs would be sufficiently sensitive. Also, by using CNTs, the thermal noise contribution might be reduced thus increasing the S/N ratio. Indeed, reduced electron-phonon coupling in quasi one-dimensional CNTs will possibly reduce the thermally induced current and enable higher detector operational temperatures without cooling systems. This would greatly simplify the design of the IR imager.

<u>Photo-conductor configuration</u>

A simplified representation of a proposed IR FPA based on CNTs is presented in Fig. 1. First, a metallic catalyst (Ni) is deposited on a barrier layer (thin film of TiN, not shown), using a doped silicon as a substrate, which also serves as the bottom electrode. The metallic thin film of catalyst is then patterned by photolithography in order to form and define the pixels. CNTs are grown to form the photo-conducting layer. The CNTs will only grow on the catalyst, respecting the pixel geometry. As a result, independent pixels having CNTs will be obtained. By using soft RF sputtering, a conducting, thin film (we will first use Au) will be deposited on top of the CNTs. The film is then patterned using photolithography. In this configuration, each pixel is made of large number of CNTs. During the operation, the active CNT layer acts as a photoconductor. A bias voltage may be applied to the top and bottom electrodes, producing a current. When IR photons are absorbed by the CNTs, it is expected that the electron-hole pairs created will increase this current proportionally to the incident radiation flux. In order to have a low noise contribution, the dark current (current when no light is incident on the detector) must be low. To achieve this, the amorphous carbon content in the CNT layer must be low.

Challenges/risks:

- Controlling the growth of the CNT with respect to diameter, length, density…
- Obtaining growth at low temperature, ideally below 450°C, for post-CMOS process compatibility.
- Avoiding shorting the top and bottom electrodes because of the presence of metallic CNTs. Possible solution is to “snap” the metallic CNTs by using a high current.
- Eliminating amorphous carbon.
- Differentiating between photo-electric effects and a possible bolometric response (change of electrical resistance with temperature).

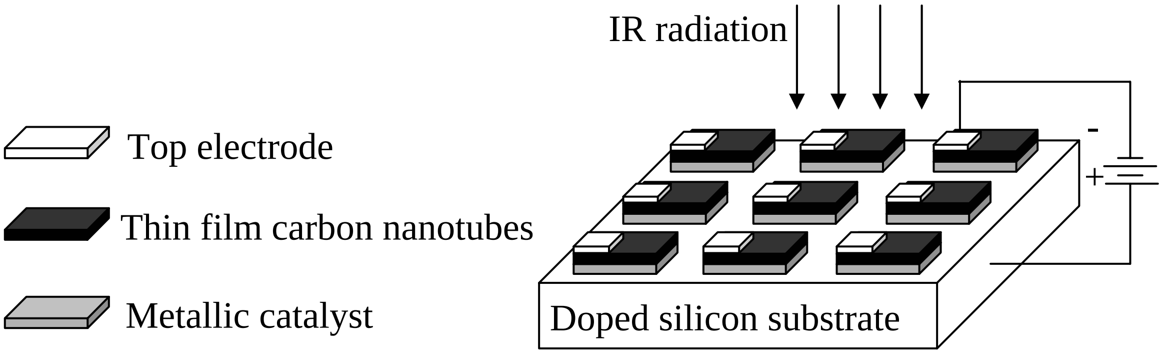


***Figure 1**. Simplified representation of an IR FPA based on carbon nanotubes*

Field-emission configuration

Another possible configuration for a CNT IR detector is presented in Fig. 2. As for display applications, it uses proven electron field-emission properties of carbon nanotubes, but a much lower extraction voltage (V_{CNT} - $V_{MCP\text{-}in}$) would be used in order to minimize noise levels (dark current). IR radiation incident on the CNTs would cause an increase in electron emission through localized heating of the CNTs or by direct photo-excitation. The emitted electrons would then hit a multi-channel plate (MCP) and be multiplied (gain determined by $V_{MCP\text{-}in}$ - $V_{MCP\text{-}out}$). These electrons would then bombard a phosphor screen where they would be converted in visible light.

Advantages of this configuration include:
- Possibility of a direct-view system in the IR leading to compact and low-cost soldier surveillance sytems.
- Contact issues are avoided.
- The presence of metallic CNTs (good field emitters) is desired.
- Resolution is limited by MCP and/or diffraction.

Challenges/Risks:
- Need for vertical growth of CNTs.
- Unknown IR photon-electron conversion efficiency.
- Contribution of thermal emission, do we need cooling?

Suggested simulation work

- For configuration 1, evaluate the photoconductive response, possible bolometric response and thermal noise contribution.

- For configuration 2, evaluate the field-emission change with respect to temperature.

Milestones

- Micro-fabrication of CNT IR detector (photo-conductor configuration).
- Evaluation of the photo-conductive response of a CNT IR detector.
- Determine whether the field-emission configuration will work.
- Evaluate the feasibility of a CNT IR detector focal plane array.

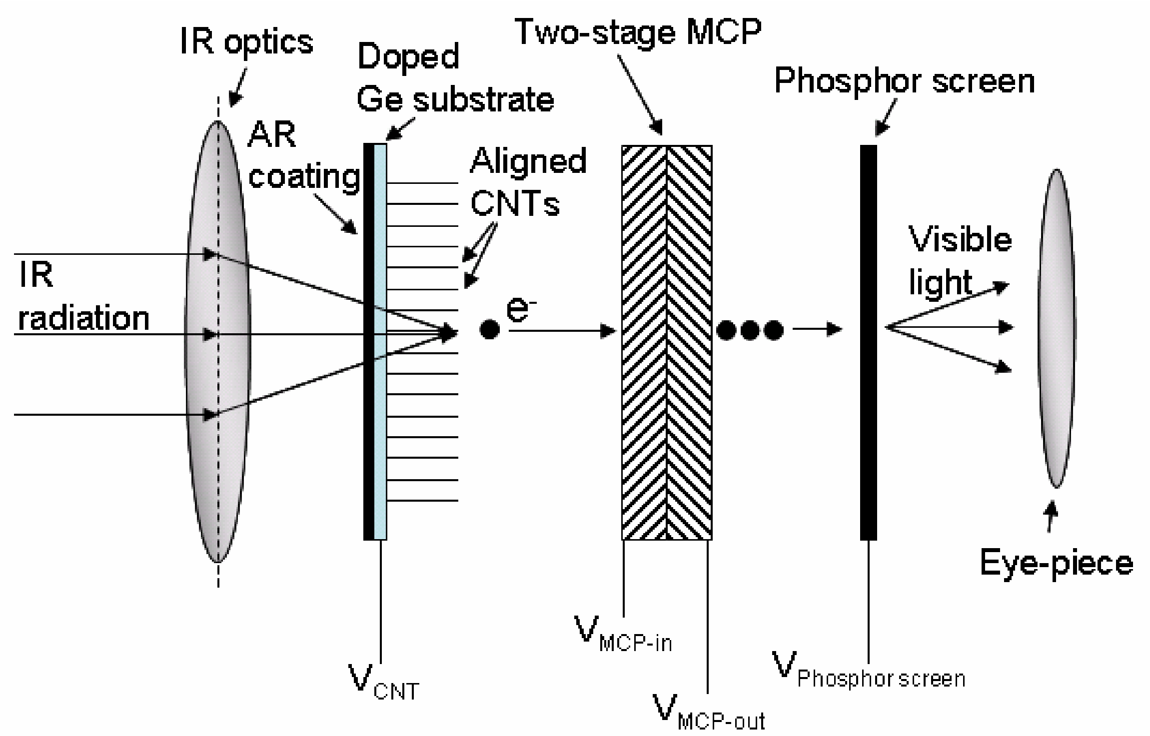


Figure 2. *Field-emission configuration of the CNT IR imager*

Carbon nanotubes (CNTs) for detection and THz detection
Project leader: USA

Goal: Consider technologies that utilize the properties of individual CNTs, either singly or arrayed in groups, for chemical and biological defense applications.

As part of the Transformational Countermeasures Technology Initiative (TCTI), the Joint Science and Technology Office for Chemical and Biological Defense (JSTO-CBD) is seeking to identify, adopt and adapt emerging and revolutionary sciences for Chemical and Biological Defense and to integrate revolutionary technologies (nanotechnology-biotechnology-information technology-cognitive sciences) across all the capability areas to transform the physical science and technology (S&T) program and to make CBR weapons ineffective.

As part of this endeavor, we are pursuing research projects that use single-walled carbon nanotubes for detection, (as well as integrated protection and decontamination applications) relevant to chemical and biological defense. We are particularly interested in nanoscale manufacturing of CNT materials for such applications.

The JSTO-CBD's Detection Capability area in interested in exploiting signatures in the THz region of the EM spectrum for chemical and biological defense applications. Currently no funded programs involve CNTs.

Currently funded projects include:

Nanofilament-Based Combined C/B Detectors

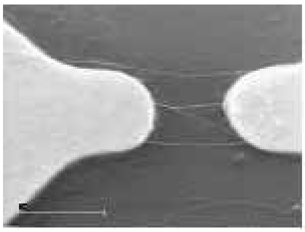
Objective: Develop science base for combined C/B sensors based on nanofilaments such as carbon nanotubes and Si nanowires.

Description of Effort: Chemically modify and assemble nanofilaments to selectively interact with C/B analytes. Detect interactions by electrical conductivity (ChemFET) and/or mechanical resonance. Determine potential for sensitivity and selectivity with multiple detecting elements.

Benefits of Proposed Technology: Improved detection of CB warfare agents; better understanding of nanosensor technology for integrated sensing of chemicals

Challenges:

- Selective interaction of nanofilaments and chemical and biological species
- Development of nano-scale testing methodology and apparatus
- Fabrication of nano-scale test devices



Carbon nanotubes deposited by dielectrophoresis between metal electrodes (Pehrsson et al)
(Marker = 1μm)

Milestones:

- **Year 1**: Investigate electrical and magnetic resonance response of at least three differently functionalized nanofilaments to adsorption of chemicals
- **Year 2**: Demonstrate simultaneous detection of multiple (3/2) CB agents with nanofilament arrays of ≥10 detecting elements.

PI: Dr. Pehr E. Pehrsson, Chemistry Division, Naval Research Lab, (202) 767-3579, (Pehrsson@ccs.nrl.navy.mil).

Fundamental Investigations of the Physics and Chemistry of DNA-decorated Carbon Nanotubes

Objective: Fundamental scientific understanding of the hybrid organic/inorganic nanostructure consisting of single-stranded DNA adsorbed on single walled carbon nanotube. Predictive computational models for nucleic acid sequence design such that the hybrid nanostructure has desired physical and chemical properties.

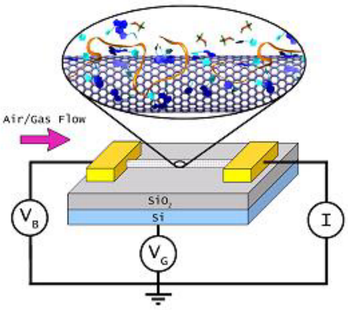
Description of Effort: Arrays of CVD-grown CNT FETs, decorated with ss-DNA of defined base sequence. Multiple micro-analysis methods (AFM, SEM, TEM, micro-Raman, x-ray diffraction, electrical conductivity) to develop a structural and electronic basis for understanding the hybrid nanostructure.

Benefit to warfighter: Basis for design of: vapor- and liquid-phase bio-molecular sensors; high performance composites; enriched suspensions of nanotubes for nanoelectronic systems.

Challenges:

- Elucidate *ss*-DNA/CNT interaction
- Discover design principles for optimum ss-DNA sequence for specific applications

Schematic of device design.



Milestones

- **Year 1**: Multiplexed electronic measurements system. FET arrays for use with robotic microarray spotter. Development and initial implementation of high throughput measurement techniques and MD simulation algorithms. Specular x-ray reflectivity measurements.

- **Year 2**: XRD of ss-DNA on graphite. 50 oligomers screened. Quantitative comparison of measured and simulated structures. High throughput measurement of ss-DNA/CNT interactions for varying sequences. Isolate factors controlling ss-DNA conformation, electronic interaction with CNTs. Resonance (“anomalous”) x-ray reflectivity measurements.
- **Year 3**: 200 ss-DNA sequences screened. XRD of ss-DNA adsorbed on aligned CNT fibers. Quantitative comparison of measured and simulated electronic properties. Refinement of MD simulations. Grazing incidence x-ray diffraction measurements. Design of sequences for desired properties of ss-DNA/CNT complex. Extension of methods to other nucleic acids.

PI contact info Prof. A.T. Charlie Johnson, (215) 898-9325, cjohnson@physics.upenn.edu

Final Product: Report on the possibilities of individual CNTs used in sensing applications, with an emphasis on chemical and biological defense applications.

Single Photon Sources and detectors
Project Leader: UK

Summary

We are proposing a project aimed at developing the under-pinning technology required to enable the realisation of the surface acoustic wave (SAW) single photon source, as proposed by Foden *et al* [1]. In particular, the aim of this programme is to develop technology that will allow such a source to emit in the technologically important 3-12 µm wavelength region. In parallel, we will assess suitable single photon detectors that could be used for this wavelength range [2]. In combination, development of these sources and detectors would enable long distance free-space, secure communication, via quantum cryptography.

In the proposed SAW single photon source (shown schematically in Figure 1), electrons trapped in the potential wells associated with a travelling SAW, propagating on a piezoelectric substrate, are forced through an electrostatic constriction (a "split-gate") such that one, and only one, single electron remains trapped in each potential well. To ensure that only single electrons at a time are allowed through the constriction the electrons have to be confined to a 2D plane parallel to the surface, which is achieved by trapping them in a semiconductor quantum well. The single electrons are then injected into the p-type region of a lateral n-i-p junction, and the latter is therefore the fundamental building block of the SAW single photon source and the focus of this proposed project. However, the transition between the n and p regions must be gradual to ensure that the SAW potential is sufficient to confine single electrons. Unlike other single photon sources under investigation, this electrically driven single photon source would offer the prospect of relatively high frequency operation in the GHz range.

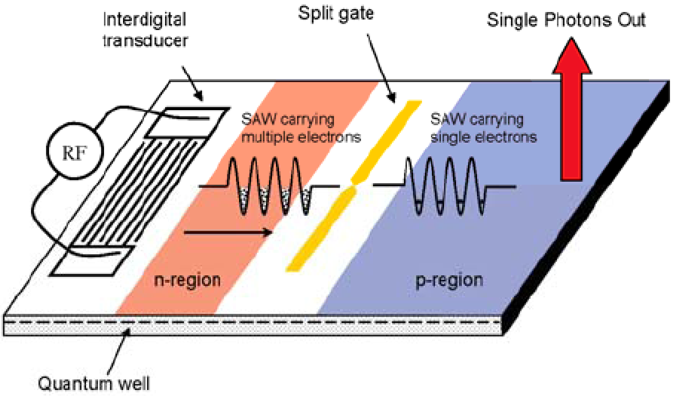


Figure 1: Schematic diagram of the SAW single photon source

The goals of the project are therefore to: (1) demonstrate an acoustically driven lateral InSb quantum well LED and (2) fabricate lateral n-i-p junctions in cadmium mercury telluride (CMT) quantum wells, using a novel technique based on layer design and bevel etching [3]. This technique is based on the growth of quantum wells with n-type doping below the well and higher p-type doping above the well. Bevel etching is used to remove the doped p-type layer above the quantum well. Where the p-type layer in intact, the well will be n-type. Where the p-type layer is etched away, the well will be n-type. In between these areas there will be an n-i-p junction. Significantly, the use of bevel etching means that these layers do not have to be etched to great precision;

somewhere along the direction of the bevel a semiconductor structure having the requisite thickness, and therefore band configuration, will inherently exist.

At QinetiQ we have already used this technique to fabricate lateral light emitting diodes in InSb [4]. The work in this project will be aimed at increasing the efficiency of these devices so that they can be integrated LED with the necessary SAW technology to produce an acoustically driven lateral LED, the key building block of the SAW single photon source. Whilst relatively little work has been reported on the growth of CMT quantum wells, as compared to III-V based quantum wells, this material system has a number of unique properties that make it highly attractive for a wide range of optoelectronic device applications. For example, it has a direct band gap that can be tuned from 0-1.5eV by varying the alloy composition, therefore allowing the fabrication of optoelectronic devices that cover the infrared spectrum from 1.5µm to 12µm.

Motivation

The development of true single photon sources is of fundamental scientific and technological importance. Although modulated lasers have been used to successfully transmit quantum keys over relatively short distances in free space, it has been shown that this method of transmission is insecure from certain types of eavesdropping attack, due to the inevitable emission of pulses containing more than one photon. In addition, it is standard to modulate the source until, on average, each pulse contains 0.1 photons (to limit the chances of two photon emission), which therefore reduces the effective bit rate by a factor of ten. The electrically driven SAW single photon source would offer the prospect for relatively high GHz frequency operation, and therefore high bit-rate. A single photon source operating in the mid-infrared could therefore be used to achieve secure, long distance, free space communication, via quantum key distribution ("quantum cryptography"), at wavelengths that exhibit favourable characteristics. These include low atmospheric scattering and absorption [5]. It also offers the prospect of being able to produce many parallel photon trains, so that brightness standards for metrology could be produced. Such standards are required to calibrate instruments and devices that operate within the infrared region.

Project Plan

The project will address several topics that have to be investigated in order to create the necessary prerequisites for the intended device applications. The project will be divided into workpackages related to the objectives described below. These are quantum well growth, vertical diode fabrication, lateral junction fabrication, and detector assessment.

WP1 CMT Quantum Well Growth

Initially, work will focus on the growth of high mobility single quantum wells, that are doped either n-type or p-type, by FFI. The structures will be grown by Molecular Beam Epitaxy, and will be designed using self-consistent models already established for other narrow gap material systems by QinetiQ and FFI. The effect of the substrate temperature on the formation of both twinning and the formation of other defects will be investigated, and also the limits to the amount of inter-diffusion between layers. FFI and partners will undertake the necessary transmission and scanning electron microscopy to optimise the materials growth. Although indium is now well established as a donor within this material system, another key objective will be to demonstrate that silver can be used effectively for acceptor doping in this application. In particular, to make lateral junctions the doped layers above the quantum well have to be doped p-type and FFI will investigate whether diffusion of the silver towards the surface will limit the maximum doping that can be achieved. In parallel, QinetiQ will develop the processes required for the deposition of electrical contacts. Although this is a non-trivial exercise, QinetiQ has extensive experience in fabricating CMT and other narrow-gap devices, and will start with processes already used for standard and quantum well devices. **Milestone 1**: Measurement of conduction through a single CMT quantum well.

WP2 CMT Vertical Diode Fabrication: The second key step will be to design, fabricate and test diode structures that include both n-type and p-type doping and determine the effect that this has on the quality of the quantum wells. Initially, conventional vertical diodes, with the p-type layer on top, will be fabricated and their electrical and optical properties assessed. Again, the structures will be designed by QinetiQ and FFI using self-consistent models. **Milestone 2**: Fabrication of a CMT quantum well LED.

WP3 CMT and InSb Quantum Well Lateral Diodes Fabrication: QinetiQ will apply its novel fabrication technique to fabricate lateral junctions, and electrical contacts will be deposited. The lateral junction diodes will be assessed both electrically and optically. In particular, we will assess the reproducibility of the fabrication process, and also investigate the degree of control that can be achieved in the positioning of the junction. This will be done with the ultimate fabrication of the SAW single photon source in mind. For the InSb devices, a range of surface processing techniques will be tried to improve the quantum efficiency of the devices, with the aim of applying the same techniques to the CMT devices as they mature. **Milestone 3:** Fabrication of a lateral CMT quantum well LED. **Milestone 4**: Demonstration of a lateral InSb quantum well LED with quantum efficiency approaching 1%.

WP4 Acoustically Driven Lateral InSb Quantum Well LEDs: The necessary SAW technology (interdigital transducers and associated instrumentation) will be applied to the lateral InSb quantum well LEDs, with the aim of demonstrating acoustically driven light emission. QinetiQ has already demonstrated that the SAW can move charge from the n-type to the p-type region of these diodes [6], and improvements to their efficiency, coupled to the use of better detectors (see below) will make this demonstration possible. **Milestone 5:** Demonstration of an acoustically driven lateral LED.

WP5 Detector Assessment: Commercial single photon detectors based on silicon avalanche photodiodes, operating at room temperature, are available with very good performance in the range 600-900nm. For example, the Perkin Elmer single photon counting module SPCM-AQR has a high detection quantum efficiency of around 60%, a low dark current of below ~500 counts per second, and a sub-nanosecond timing resolution. However, at longer wavelengths the performance of these diodes deteriorates rapidly, due to the poor absorption coefficient of silicon, so that at 1060nm the quantum efficiency is less than 20%. However, there here have been rapid developments in superconducting detectors [2], which has led to a recent demonstration of single photon counting in the mid-infrared. QinetiQ will assess these detector, when cryogenically cooled, with the aim of assembling a Hanbury-Brown Twiss apparatus for the detection of single photons in this wavelength range.

WP5 SAW Detector Assessment: USA (AFRL) will write a report on photon counting detectors that utilise SAWs.

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