Novel Quantum Dot based Approach for Biosensing*

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***Abstract* - Arrays of epitaxial quantum dots (QD), which have been known for their applications in advanced communication devices such as QD lasers, have been proposed as a novel platform for the development of optical bio-sensors capable of rapidly detecting numerous pathogenic substances.**

I. INTRODUCTION

Bright photoluminescence (PL), small diameter (< 10 nm) and unique properties of semiconductor nanocrystals, also known as colloidal quantum dots (cQD), have made them an attractive material system for developing new bio-imaging technologies and a new generation of devices for bio-detection. The driving force behind this interest is the ability of cQD, in contrast to fluorescent dyes, to yield theoretically unbleachable PL. Also, different wavelength emitting cQD could be excited with a single wavelength excitation source which would greatly simplify the measuring schemes of cQD-based bio-detection. Commercially available colloidal CdSe QDs emit in the 500 to 650 nm range,[1,2] thus, they are attractive for inspection in the visible range of the human eye. However, for *in-vivo* investigation of human organs and tissues, it would be advantageous to have material emitting in the 800 – 1100 nm range, which falls in the window of the minimum optical absorption of combined human blood, tissue and water. Efficient and cost-effective cQD's for such applications have yet to be developed. Development of cQD's compatible with different bio-environments or functionalized for chemisorption of specific biomolecules remains one of the key challenges faced by today's nanoscience and technology. For instance, critical to the bright and stable PL of cQD's is the ability to minimize the role of surface defects, which are the source of quenching the PL signal through the non-radiative carrier recombination (NRCR) effect. The neutralization of surface defects requires the development of ever elusive, reproducible surface processing methods. The free-standing nature of cQD's makes it difficult to implement otherwise powerful dry methods of processing such as laser-assisted etching and surface functionalization.

To address some of the problems related to the technology of cQD's, we have proposed an alternative method of using quantum dots for bio-detection that is based on the application of arrays of epitaxially grown quantum dots (eQD). A typical eQD device for such an application would consist of a line or an array of pixels of eQD's emitting at a determined wavelength, or at wavelengths that could be made site dependent. It is relevant to mention that eQD's, unlike cQD's, do not exhibit a sensitivity-reducing blinking effect. In addition, they can be processed with specialty tools, which are impractical for cQD's, allowing to tune the emission wavelength of an individual eQD or groups of eQD's and to carry out selective area surface passivation/functionalization for immobilization of different antibodies. Consequently, we have initiated a study of bio-sensing based on InAs eQD's. In this way, we could take advantage of advanced technologies available for the fabrication of these quantum dots. Also, working on a device with a strong emission in the near-infrared region is especially attractive for bio-detection *in-vivo*. A schematic diagram of a possible eQD device is illustrated in Fig. 1.

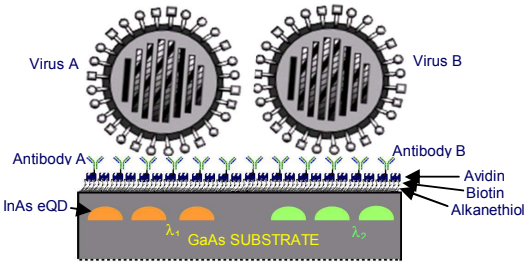

Fig. 1. A schematic diagram of the eQD device for simultaneous detection of different pathogens.

One of the fundamental requirements concerning this development concerns understanding the process of bio-functionalization of GaAs – the material used for capping InAs eQD's. The choice has been made to construct an innovative bio-architecture based on the GaAs-thiol-biotin-avidin interface.

II. EXPERIMENTAL DETAILS

The first group of samples of *p*-type (001)GaAs was exposed to five long chain thiols: 1-hexadecanethiol (HDT, $HS(CH_2)_{15}CH_3$), 16-mercaptohexadecanoic acid (MHDA, $HS(CH_2)_{15}CO_2H$), 1-undecanethiol (UDT, $HS(CH_2)_{10}CH_3$), 11-mercapto-1-undecanol (MUDO, $HS(CH_2)_{11}OH$) and 11-mercaptoundecanoic acid (MUDA, $HS(CH_2)_{10}CO_2H$). In addition, we investigated a sample coated with Cysteamine (CYS, $HS(CH_2)_2NH_2$), which represents a case of a short-chain thiol. The investigated thiols are terminated either with hydrophobic (CH_3) or hydrophilic (CO_2H, OH, NH_2) terminal

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groups. Another group of samples of undoped (001)GaAs was exposed, sequentially, to the 11-amino-1-undecanethiol ($HS(CH_2)_{11}NH_2$), biotin and avidin (from egg white).

The attenuated total reflection-Fourier transform infrared (ATR-FTIR) spectra were collected for p-polarized radiation in the energy range of 600 to 6000 cm^{-1}. The configuration and details of these measurements have been reported earlier.[3] Room-temperature PL mapping, fluorescence microscopy, x-ray photoelectron spectroscopy and some other surface sensitive techniques have been implemented to study thiolated and bio-functionalized samples with the aim of determining the effect of surface passivation, its stability and efficiency in binding selected biomolecules.[4-8]

III. Results and discussion

The ATR-FTIR measurements suggest that for a hydrophilic GaAs substrate, methylene chains with terminal hydrophobic groups are relatively highly ordered and closely packed as they tend to be organized with a small tilted angle to the substrate normal. In contrast, methylene chains of thiols with hydrophilic terminal groups incline to be organized almost parallel to the GaAs substrate. Based on this investigation, we have established that long-methylene-chain thiols ($SH(CH_2)_nCH_3$) with $n \geq 10$ provide superior conditions for passivation of the surface of GaAs when compared to thiols with shorter methylene chains.[3-5] A study of aging and detergent washing effects in GaAs wafers passivated with hexadecanethiol, HDT ($HS(CH_2)_{15}CH_3$) was carried out with PL measured from GaAs at room-temperature as a function of time, up to 1000 hours.[9] The overall density of surface states formed on (110) GaAs was found to be significantly lower than those on (001) GaAs. The strong increase of the PL signal after detergent washing of (001) GaAs suggests that this treatment is effective in the removal of some of the NRCR-type defects. The 19-fold enhancement of the PL signal, in comparison to that of the oxidized sample, has been obtained by using GaAs that, following the etching and detergent washing procedures, was thiolated with HDT.

The GaAs thiolation experiments allowed us to determine conditions for the successful immobilization of avidin on (001) GaAs.[6] Using fluorescence microscopy, atomic force microscopy and PL measurements, we were able to confirm the robustness of the interface involving avidin. Consequently, we tested such an interface for the attachment of biotinylated and fluorescein stained polystyrene nano-beads (*b*-NB) that were investigated as objects mimicking virus attachment to the (001) GaAs surface functionalized with avidin. Experiments showed that the applied bio-architecture provided strong binding and resistance of *b*-NB to detergent washing and short ultrasonic treatment with deionized water.[7]

The preliminary *ab-initio* calculations of thiol-thiol and thiol-GaAs interactions have provided important insight into this relatively poorly known material system.[10] We have found that the calculated binding energy of thiolate to As-rich GaAs (001) surface is 2.114 eV. This compares to 1.64–2.3 eV reported for Au (111) and 2.19 eV for Cu (111) surfaces calculated using a similar theoretical technique. The calculations support our observations concerning the stability of biomolecules immobilized on the surface of GaAs *via* thiol interface.

IV. Conclusions

We have proposed an innovative bio-architecture consisting of epitaxial quantum dots (eQD) for the development of optical bio-sensors capable of rapidly detecting numerous pathogenic substances. A typical eQD bio-sensor will consist of a line or an array of pixels of eQDs emitting at a determined wavelength, or at wavelengths that could be made site dependent. In this way, bio-detection of numerous biomolecules could be carried out simultaneously. The important conclusion of the reported research is that the strong binding energy of thiol-GaAs, which has been observed experimentally and confirmed by our theoretical calculations, places this material system at par with a well known thiol-Au system, and validates the potential of GaAs as an attractive material for binding different bio-moieties.

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