MICROANALYSIS OF QUANTUM DOTS FOR INFRARED DETECTOR APPLICATIONS

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ABSTRACT

Materials that are sensitive to mid and far infrared radiation have numerous military applications, such as chemical spectroscopy, atmospheric communication, image recognition, night vision, and land mine detection (Phillips, et al, 1998; Goldberg, et al, 2002;). In an effort to improve battlefield situational awareness, the Army is investigating multiple approaches to developing sensitive infrared detectors and focal plane arrays. The goal is to quickly detect, locate, and recognize enemy targets. These detectors need to work in either day or night, in multiple weather conditions, and be able to detect obscured and/or camouflaged targets within cluttered environments. At the Sensors & Electron Devices Directorate of the Army Research Laboratory, several materials are grown by molecular beam epitaxy (MBE) and characterized to assess their suitability for use in infrared detector devices. These materials include III-V strained layer superlattices, quantum wells and quantum dots, and II-VI semiconductors such as HgCdTe. It is yet unknown which material system will best meet the competing criteria for infrared detectors for the Army: including maximum sensitivity and robustness, minimal cooling requirements, and greatest portability. In this paper we discuss ARL's quantum dot infrared photodetector (QDIP) research, with a particular focus on the microstructural characterization of quantum dots systems that have been manipulated on a nanoscale level to tailor their electrical and optical properties.

1. INTRODUCTION

The crystalline quality of semiconductor films directly affects their performance in electronic devices. Dislocations, stacking faults, and grain boundaries may provide unintended paths for carrier transport and impurity diffusion. They may also act as recombination centers for excess carriers and degrade the electron and hole mobilities. Structures based on quantum wells or strained-layer superlattices require thin, pseudomorphic films grown to a precise thickness. In this case, materials are selected that have a low lattice mismatch with one another and layer thicknesses are grown below the critical thickness for dislocation generation. The desired growth mode is the Frank-Van der Merwe mode, which results in a two-dimensional layer-by-layer film growth.

Quantum dots arise when it is energetically favorable for the film to relax by forming three-dimensional islands rather than by forming misfit dislocations. Therefore, materials are selected that have a somewhat larger lattice mismatch with one another compared to those selected for quantum well structures. This mode of growth, known as Stranksi-Krastanov (S-K), begins with two-dimensional layer-by-layer growth of a wetting layer followed by self-assembled island formation. Discrete, three-dimensionally confined states result within the dot if the conduction band edge of the dot materials is lower than that of the surrounding matrix. Therefore, quantum dots are electronically analogous to individual atoms.

Intersubband transitions, and likewise photon absorption, can only occur for light polarized in the direction of quantization (West & Eglash, 1985). In a quantum well, the electrons are only confined in the direction perpendicular to the well. Therefore, normally incident light on a quantum well structure is not detectable. This is one of the major limitations related to Quantum Well Infrared Photodetectors (QWIPs). A polarization rotating structure, such as a diffraction grating, must be integrated into each pixel of a QWIP array. Quantum dots are confined in all three dimensions, and therefore intersubband transitions can be induced by infrared light of any polarization. This eliminates the need for complex optical coupling structures. However, the physical characteristics of the quantum dots (e.g., the size, shape, and spatial distribution) are determined primarily by the dynamics of the S-K growth mode. This makes it essentially impossible to independently choose values for these parameters in order to, for example, validate a theoretical prediction, without manipulating the growth in some way that provides control over an otherwise random process. In this paper, we use microstructural analysis techniques to examine the effects of some of these growth manipulation schemes on the crystal quality of the quantum dots and the surrounding matrix materials.

Since each quantum dot is a potential absorber, it is desirable to grow a film having a high density of dots. Furthermore, the dots need to be buried in order to induce quantum confinement within the dot. To achieve these goals, quantum dots are often grown in a superlattice structure consisting of alternating layers of quantum dots and the matrix material. The number of dots in the structure increases with each superlattice period, but growing too many periods may result in the formation of strain relieving dislocations.

We are examining numerous III-V binary and ternary alloys for use in the quantum dots and the surrounding matrix. To date we have grown quantum dot superlattice structures on both GaAs and InP substrates. Use of bandgap engineering, which exploits the energy band lineups between selected materials, allows us to customize device properties for specific applications (such as long wavelength, mid-wavelength, and two-color detectors).

2. SUMMARY OF CURRENT RESULTS

One system under investigation at ARL consists of a superlattice structure of alternating layers of InAs dots and GaAs grown on GaAs substrates. Several techniques are used to structurally characterize the dots. Atomic force microscopy (AFM) images are useful for determining the height and distribution of quantum dots on an exposed surface. The quantum dots are approximately the same size as the radius of curvature of the probe tip; therefore the lateral dimensions acquired from AFM are larger than reality. Scanning electron microscopy (SEM) is useful for examining the quantum dot densities and can estimate their lateral size. Both SEM and AFM are unable to examine quantum dots that have been buried within a matrix.

Transmission electron microscopy (TEM) is used in addition to AFM or SEM to more fully characterize quantum dot structures. Accurate dot heights are obtained by imaging atomic monolayers in high resolution. The crystalline quality of the dot, the wetting layer, the matrix, and their accompanying interfaces is directly observed with TEM (Fig. 1). The quantum dot distribution throughout the superlattice can be observed with low-resolution imaging (Fig. 2). Limitations of TEM arise from the two-dimensional images resulting from a three dimensional sample. All information collected in a TEM is an average of everything the electron beam sees as it penetrates the sample.

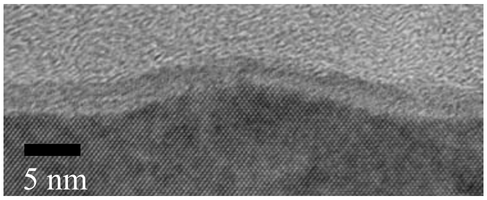

Fig. 1. TEM image of InAs of a single quantum dot grown on GaAs. The dot's height is 36 Å and its width is 24.5 nm.

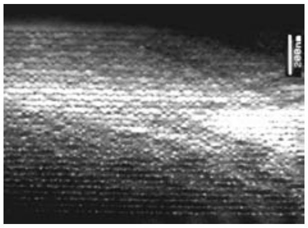

Fig. 2. Low resolution image of an InAs QD/GaAs superlattice.

We are currently examining strain balanced quantum dot superlattices that consist of binary dots within ternary matrices. Strain balancing is achieved by adjusting the mole fractions of the matrix material to compensate for the compressive strain induced by the dots. The goal is to be able to grow many superlattice periods without generating strain-relieving dislocations. We are also examining MBE growth manipulation techniques for controlling the size, density, and distribution of the quantum dots. One such manipulation under investigation includes partially burying the dots and subsequently growing more dots in order to independently change lateral and vertical dot dimensions. These details will be discussed in the full version of this paper.

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