Waveguiding in an InAs Quantum Dots Nanomaterial for Scintillation Applications

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Abstract : InAs Quantum Dots (QDs) in a GaAs matrix is a well-documented luminescent material with high light yield, as well as thermal and ionizing radiation tolerance due to quantum confinement. These benefits can be leveraged for high-efficiency, room temperature scintillation detectors. The proposed scintillator is composed of InAs QDs acting as luminescence centers in a GaAs stopping medium, which also acts as a waveguide. This system has appealing potential properties, including high light yield (~240,000 photons/MeV) and fast capture of photoelectrons (2-5ps), orders of magnitude better than currently used inorganic scintillators, such as LYSO or BaF2. The high refractive index of the GaAs matrix (n=3.4) ensures light emitted by the QDs is waveguided, which can be collected by an integrated photodiode (PD). Scintillation structures were grown using Molecular Beam Epitaxy (MBE) and consist of thick GaAs waveguiding layers with embedded sheets of modulation p-type doped InAs QDs. An AlAs sacrificial layer is grown between the waveguide and the GaAs substrate for epitaxial lift-off to separate the scintillator film and transfer it to a low-index substrate for waveguiding measurements. One consideration when using a low-density material like GaAs (~5.32 g/cm^3) as a stopping medium is the matrix thickness in the dimension of radiation collection. Therefore, luminescence properties of very thick (4-20 microns) waveguides with up to 100 QD layers were studied. The optimization of the medium included QD shape, density, doping, and AlGaAs barriers at the waveguide surfaces to prevent non-radiative recombination. To characterize the efficiency of QD luminescence, low temperature photoluminescence (PL) (77-450 K) was measured and fitted using a kinetic model. The PL intensity degrades by only 40% at RT, with an activation energy for electron escape from QDs to the barrier of ~60 meV. Attenuation within the waveguide (WG) is a limiting factor for the lateral size of a scintillation detector, so PL spectroscopy in the waveguiding configuration was studied. Spectra were measured while the laser (630 nm) excitation point was scanned away from the collecting fiber coupled to the edge of the WG. The QD ground state PL peak at 1.04 eV (1190 nm) was inhomogeneously broadened with FWHM of 28 meV (33 nm) and showed a distinct red-shift due to self-absorption in the QDs. Attenuation stabilized after traveling over 1 mm through the WG, at about 3 cm^{-1}. Finally, a scintillator sample was used to test detection and evaluate timing characteristics using 5.5 MeV alpha particles. With a 2D waveguide and a small area of integrated PD, the collected charge averaged 8.4 x10^4 electrons, corresponding to a collection efficiency of about 7%. The scintillation response had 80 ps noise-limited time resolution and a QD decay time of 0.6 ns. The data confirms unique properties of this scintillation detector which can be potentially much faster than any currently used inorganic scintillator.

Keywords : GaAs, InAs, molecular beam epitaxy, quantum dots, III-V semiconductor
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