

Ultrafast InAs Quantum Dot Scintillation Detector

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High-efficiency, picosecond scintillation detectors are critically needed for many applications, particularly in the fields of medical imaging, high energy physics and nuclear security. Recently, we proposed a design and considerations for a semiconductor scintillator composed of InAs Quantum Dots (QD) acting as luminescence centers in a GaAs stopping matrix/waveguide, integrated with a photodetector grown epitaxially on top of the waveguide (WG) [1]. This material has appealing potential photonic properties including high light yield ($\sim 240,000$ photons/MeV) due to the narrow semiconductor bandgap, fast capture of electrons in QDs (2-5ps) and high radiation hardness ($>10^4$ Gy). The high refractive index of GaAs ($n=3.4$) ensures light emitted by the QD's is waveguided within the GaAs matrix, which can then be collected by an integrated InGaAs p-i-n photodiode (PD).

A proof-of-concept integrated scintillation detector (Fig. 1) was grown using molecular beam epitaxy on a GaAs substrate. It has a 20 μm thick GaAs layer with embedded sheets of modulation p-type doped InAs QDs. A generic excitation source is shown interacting with the GaAs matrix, resulting in QD luminescence, which is then waveguided towards an InGaAs PD, grown on top of the WG and tuned to the QD luminescence band (~ 1150 nm). Employing QD structure engineering improves the internal efficiency of the QD luminescence to $\sim 60\%$ at room temperature and reduces overall waveguide attenuation to about $3\text{-}4\text{ cm}^{-1}$.

A sample, as shown in Fig. 1, was used to evaluate the timing characteristics of 5.5 MeV alpha particle responses. The

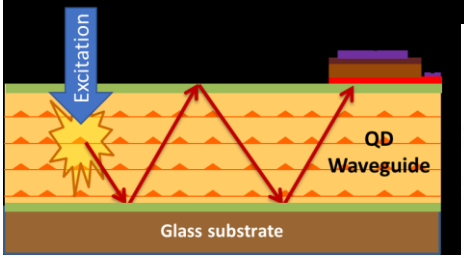


Fig. 1. A schematic of an InAs QD/GaAs integrated scintillation detector illustrating the operation conceptually: QD luminescence being waveguided to an InGaAs photodetector, which is monolithically integrated on the epitaxially grown WG.

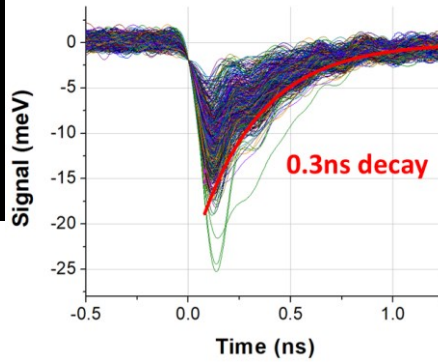


Fig. 2. Recorded pulses from 5.5 MeV alpha particles emitted by Am^{241} , positioned roughly 1 cm above the WG. Decay time is measured as 0.3 ns.

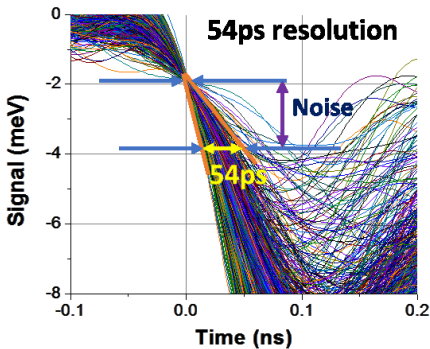


Fig. 3. Close-up profile of alpha particle response leading edge from Fig. 2, with jitter measured as ~ 54 ps.

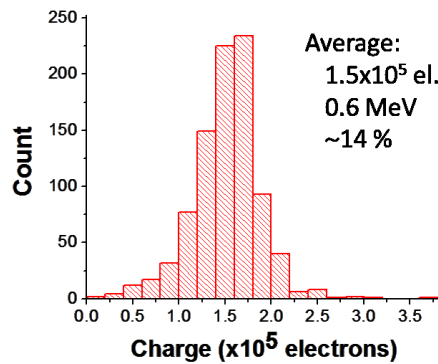


Fig. 4. Histogram of a collected charge and corresponding energy from 1000 pulses averaging 14% of 4.5 MeV deposited energy (assuming 1 MeV of alpha-particle energy is lost by air ionization).

source had a radioactivity of 1 μC , suspended in air approximately 1 cm above the QD waveguide. The scintillation response (Fig. 2) had decay time of 0.3 ns, corresponding to QD recombination time and a noise-limited time resolution of 54 ps (Fig. 3). With a 2D waveguide and an integrated PD covering only 16% of the WG width, the collected charge averaged 1.5×10^5 electrons (Fig. 4), corresponding to a collection efficiency of about 14%. This can be estimated as 34,000 photoelectrons per 1 MeV of incident energy, given about 1 eV of alpha particle energy loss in air. This data confirms the unique photonic properties of this scintillation detector, which has the potential to be much faster than any currently used inorganic scintillator.

Additionally, technologies for fabricating an epitaxial film from substrate and bonding multiple waveguides using organic adhesives are tested and evaluated.

[1] S. Oktyabrsky, et al. "Integrated Semiconductor Quantum Dot Scintillation Detector: Ultimate Limit for Speed and Light Yield," *IEEE TNS*, **63**, 656 (2016).