Exploration of charged particle tracking using InAs quantum dots in GaAs semiconductor matrix

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Charged particle tracking will continue to be a major challenge in current and next generation high-energy physics experiments. While silicon based technologies have continuously met each new round of instrumentation requirements and challenges, other technologies may offer considerable performance improvements and should be explored. One possible avenue for innovation is the study of charged-particle tracking with novel ultrafast scintillating material utilizing semiconductor stopping media with embedded quantum dots.

Timing resolution better than 10 ps is one of the most important requirements for tracking detectors at future collider experiments [1]. Achieving this with solid state tracking sensors based on the electron drift in semiconductors appears to be challenging due to the limited drift velocity of the charge carriers. In this Letter, we discuss an alternative technology by substituting relatively slow electric charge collection with fast optical signal collection in novel ultrafast integrated scintillation detectors [2–4].

We propose to explore planar tracking sensors that produce scintillation light detected by low capacitance integrated photodiodes. Fabrication of such a sensor requires a scintillator with unique properties—very high light yield and a fast emission time. We have identified a candidate sensor material based on self-assembled InAs quantum dots (QDs) embedded into a GaAs matrix for such a detector [2]. QDs are known to be excellent light emitters with close to 100% efficiency and emission times of about 500 ps. To make a scintillator, however, one needs to embed QDs into a dense medium that is transparent to the QD photon emission. GaAs fulfills this requirement.

We envision the proposed tracking sensor as two integrated physical systems:

1. The scintillator: A charged particle travels through the InAs QD/GaAs scintillator and produces electron-hole pairs in the GaAs matrix (2.4×10^5 pairs per MeV). The carriers are fast captured (2-5 ps) in the positively charged QDs due to high electron mobility of up to 8500 $\mathrm{cm}^2/\mathrm{Vs}$ at room temperature. The infrared emission (1.1 eV photons) is red-shifted > 300 mV from the bandgap of the GaAs matrix, resulting in low self-absorption ($\sim 1\ \mathrm{cm}^{-1}$) [3]. Thus the scintillator is practically transparent to the scintillation light at the ranges targeted by the particle tracker of less than a few mm.

2. The photodetectors: As the refraction index of GaAs is high at about 3.4, only $\sim 2\%$ of the emitted light exits the scintillator through one planar interface with air, and the rest gets reflected and travels inside the scintillator. Thus for efficient detection, the photodetector (PD) must be physically integrated with the scintillator. The proposed design has a matrix of InGaAs photodiodes fabricated directly on the surface of the scintillation matrix. Photodiode thickness is of the order of 1–2 microns, leading to efficient absorption of the QD emission. Photodiodes fully cover the scintillator area, resulting in a uniform and efficient collection of the emitted light with close to unity fill factor.

A schematic drawing showing this proposed sensor system is shown in Fig. 1.

Another important integrated block is a Si readout circuit providing low-capacitance load and adequate signal-to-noise ratio. This system is envisioned as an ASIC packaged with the scintillation detector on a common submount in order to minimize integration parasitics. The importance of the integrated preamplifier/signal processor arrays is illustrated by our recent results summarized below.

Given that electron-hole production in GaAs occurs at about 4.2 eV, we expect an InAs/GaAs semiconductor scintillator to have a light yield of about 2×10^5 photons/MeV—much higher than the light yield of the best known inorganic scintillators. InAs/GaAs scintillators are grown as thin wafers. During the growth procedure, the minimization of the strain energy due to the different lattice constants of InAs and GaAs leads to formation of stable 10 nanometers scale InAs islands, yielding QDs. The procedure is then repeated, leading to a multi-layer structure alternating between layers of GaAs matrix and InAs QDs. Details on the InAs/GaAs structure growth can be found in Ref. [3, 4].

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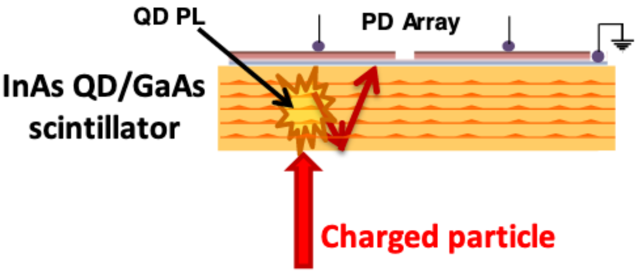

FIG. 1. A schematic drawing the of the proposed tracking sensor. A charged particle enters the GaAs scintillator, producing electron-hole pairs. The electrons then quickly interact with the postively charged InAs quantum dots (QDs). The QDs undergo photoluminescence (PL) and emit photons that travel through the medium. The emitted photons are collected by a photodiode (PD) array.

The first prototype sensors have been produced at SUNY Polytechnic Institute at Albany as thin wafers of ~ 20 micron thickness with integrated small area PDs. The measurements of single-channel performance with α particles have been published in Ref. [3, 4] and recently presented at CPAD 2019 [5]. Using Am^{241} α-sources (5.5 MeV) and fast preamplifiers, we have seen fast decay constant of 300 ps, and a 70 ps time resolution (limited by circuit noise and bandwidth) with a collection efficiency of 1.7×10^4 electrons per 1 MeV of deposited energy. Alternatively, a slower low-noise preamplifier demonstrated 5.1×10^4 electrons/MeV of incident energy with longer ~ 6 ns pulses. We expect the proposed tracker geometry will provide close to theoretical 2×10^5 electrons/MeV efficiency.

A typical photodiode bias voltage is of the order of 1.5–2 V; it can also operate without external bias in a photovoltaic mode. Thus the sensor requires power mostly for the readout electronics, in contrast to high voltage sources needed for Si drift detectors.

We do expect significant research and development challenges. For example, when a minimum-ionizing particle crosses a 20 micron thick QD-GaAs scintillator, it produces about 4000 electron-hole pairs. Thus, detection of minimum ionizing particles will require measurements of signals corresponding to a few thousand electrons collected over the time of about 500 ps. We intend to address these challenges and believe that this effort would greatly benefit from community recognition and support.

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