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Large Dynamic Range, Picosecond Resolution Radiation Detection Based on Low-Temperature-Grown Epitaxial GaAs Films

D. E. Watkins*, R. S. Wagner , K. K. Khachaturyan, and J. R. Joseph

Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The original objective of the project was to develop ultrafast radiation detectors based on GaAs epilayers grown by molecular beam epitaxy at 200-300 °C. Low temperature (LT) GaAs is known to have subpicosecond carrier lifetimes; therefore, detectors based on this material should have response times of the order of 1 ps, more than an order of magnitude faster than any existing high energy radiation detectors. During the course of the project it became clear that an adequate material structure could not be attained, and therefore the emphasis of the project changed from LT-GaAs to polycrystalline chemical-vapor-deposited (CVD) diamond. This change resulted in demonstrating the feasibility of diamond microstrip detectors for high luminosity colliders for the first time. At the same time, we have advanced the state-of-the-art in diamond film quality.

1. Background and Research Objectives

The detection of radiation with picosecond temporal resolution and large dynamic range is increasingly important in such diverse applications as the nuclear weapons program, synchrotron radiation sources, and x-ray surveillance from satellites. Recent advances in growth techniques of III-V semiconductor systems enable us to explore the development of a novel class of ultrafast detectors sensitive to x-ray, γ -ray and charged-particle radiation. Detectors with response times of the order of 1ps (one to two orders of magnitude faster than any known radiation detectors) and dynamic ranges of up to two orders of magnitude greater than existing detectors could be developed. Our objective was to investigate the use of large-defect-density GaAs films combined with novel circuit structures for high temporal resolution radiation detection.

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Los Alamos has been developing fast radiation detectors since 1982. The latest achievement was the development of a radiation detector, based on neutron-irradiated bulk GaAs, that has a response time faster than 100 ps (and in some cases, as fast as 30 ps) [1]. Neutron irradiation introduces midgap states which serve as recombination centers [2]. The reduced lifetime of the free carriers increases the speed of detectors made from this material.

This radiation detector technology was selected by R&D magazine as one of the 100 most technologically significant new products of 1991. These fast high-energy radiation detectors are needed for inertial confinement fusion and pulsed-particle beam diagnostics, synchrotron experiments, nuclear-weapon diagnostics, and in soft x-ray detection. Many applications require radiation detectors with greater than four decades of dynamic range. An ideal detector for these applications should have a response time of the order of a few picoseconds, a current response proportional to the incident radiation intensity for long radiation events, and a large dynamic range.

2. Importance to LANL's Science and Technology Base and National R&D Needs

Several programs within the Laboratory have increasingly stringent requirements for the detection of radiation. Nationally, fast radiation detectors are needed for the inertial confinement fusion program, pulsed particle beam diagnostics, and synchrotron experiments. In addition, there is a vital need for soft x-ray detectors for satellite-based surveillance of compliance with nuclear test ban treaties. Our research could lead to radiation detector technology capable of meeting these needs.

3. Scientific Approach and Results

a. Materials Development

We investigated the use of epitaxial GaAs films grown by molecular beam epitaxy (MBE) at 200 to 300°C with subsequent annealing inside the MBE chamber for detector applications. As grown, LT GaAs had up to 1 percent superstoichiometric As, most of which was incorporated as As on Ga site anti-site defects. Upon annealing, the concentration of anti-site defects in LT GaAs decreased from ~1 percent to the level of the order of $10^{18}/\text{cm}^3$, which was still much higher than can be induced by neutron irradiation. As a result, free carrier lifetimes in annealed LT GaAs were often below 1 ps and values as low as ≈ 200 fs were reported.

b. Circuit Development

Because x- and γ -rays penetrate the thin epilayer into the GaAs substrate, where electron-hole pair lifetimes are long (~ 1 ns), the time response could have an undesirable long carrier decay tail. We investigated ways to minimize the substrate-related tail in the radiation-induced current to the acceptable level of ~ 1 percent of the signal during exposure to radiation and the ~ 1 ps interval afterwards. Part of the solution was to concentrate the electric field within the LT GaAs epilayer by using a periodic grating of electrodes of alternating polarity for carrier collection as shown in Fig. 1.

A p-n junction incorporated at the interface between the semi-insulating substrate and the LT GaAs epilayer blocked the carriers that originated in the substrate from crossing the interface with the epilayer. The resulting double i-p-n junction (i designates semi-insulating GaAs substrate) was impermeable to both electrons and holes, although a displacement current still existed.

The following materials and circuit parameters needed to be optimized: (i) temperature of the MBE growth of LT GaAs, which determines carrier lifetime and mobility, (ii) thickness of the epilayer and width of the interdigital electrodes (or the period of the electrode grating), and (iii) the number of electrode pairs and their length. These two parameters determined the RC time constant and the total area from which the carriers were collected. A series connection of interdigital capacitors was used to decrease the RC time constant without decreasing the collection area.

Radiation detectors were characterized using fast pulsed radiation sources in the energy range of 100 eV to 20 MeV. We routinely used the National Synchrotron Light Source at Brookhaven National Laboratory and the pulsed linear accelerator at EG&G, Santa Barbara for characterization of radiation detectors. In addition, we used pulses of 850 nm semiconductor laser light for preliminary detector evaluation.

Since the beginning of this project a number of radiation detectors have been fabricated and tested. We have found that the response time of the detectors is limited not by electron-hole recombination times (which for LT GaAs is often below 1 ps), but instead by the design-related RC time constants. Fall times as small as 10 ps on the 70-GHz Hypres superconducting oscilloscope have been obtained using a device consisting of 10 fingers 100 μ m long and 2 μ m wide separated by 2 μ m gaps. The contribution to the detector response from the substrate continues to be an issue. In a typical detector, there is a nanosecond-long tail due to interaction of electron beam with substrate with amplitude of about 10 to 30 percent of the peak signal, which is at the limit of acceptable ratios. There is a clear dependence of the tail-to-peak ratio on the LT GaAs film thickness.

In most cases the devices we have made are so fast that the measured response time corresponds closely to the instrumental limit determined by the speed of the oscilloscope and the length of the laser pulse. The speed of these detectors is already sufficient for many applications where high speed is needed and low sensitivity is acceptable.

The sensitivity observed so far is considerably lower than the sensitivity of detectors based on neutron irradiated semi-insulating GaAs that we have previously developed. Our future development efforts will be aimed at increasing the sensitivity of these thin film detectors. There is a trade-off between the sensitivity and the RC time constant which determines the speed. Indeed, increasing the sensitivity will require an increase in charge collection area. For the small period of electrode array needed to concentrate the field in the substrate, an increase in collection area can only be achieved by an increase in either the number or the length of interdigital electrodes. That, however, would lead to an increase in RC time constant and consequently slower speed.

More recently, we started developing radiation detectors based on the LT GaAs epilayers grown on the conducting n^+ GaAs substrates. We found that to eliminate the substrate contribution to the detector signal it is necessary to electrically isolate it from the epilayer by incorporating the p-n junction barrier against carrier diffusion. The structure that we used was n^+ GaAs/ p^- Al_{0.4}Ga_{0.6}As/ n^- Al_{0.4}Ga_{0.6}As/LT GaAs. We have found that it is necessary to use the interdigital electrode arrays for the carrier collection even for epilayers on conducting substrates. It was finally realized that the aforementioned approach also resulted in the carrier decay tailing. Therefore, the final approach that was attempted was the separation of the LT-GaAs epilayer from the substrate by selective etching. In the end, this approach was far more difficult than expected.

With the stated difficulties realized, we changed our course of research and development to studying and using polycrystalline, chemical-vapor-deposited (CVD) diamond for radiation detection. Also, this change in the course of the research was partly due to difficulties in obtaining the epilayers with proper material structures. In some respects, the CVD diamond film technology has a greater technological relevance due to its unique properties. With respect to the radiation detection, diamond radiation detectors have one distinct advantage over GaAs in that the charge density is greater for higher charged particle stopping power but has low atomic number for reduced interaction with high energy photons. This allows greater discrimination between charged particles and γ -rays when the charged particle detection is required with the large γ -ray background.

With the change in the nature of the R&D, we first concentrated on a position-sensitive detector for high luminosity colliders. This was motivated by the fact that the planned large hadron collider (LHC) would need an inherently rad-hard material that was also fast.

Furthermore, we were a part of a collaboration called RD42 to research the feasibility of diamond-based detectors for the planned LHC. Our R&D in collaboration with RD42 resulted in demonstrating the feasibility of diamond microstrip detectors for minimum ionizing particle tracking for the first time (Fig. 2) [3]. The position resolution of the detector was found to be about 12.8 μm (Fig. 3) with the signal-to-noise ratio of 22, which is comparable to the value for silicon microstrip detectors. Furthermore, we have also shown that polycrystalline, CVD diamond detectors to be rad-hard up to 10^{14} 300-MeV pions/cm², which is much more than silicon-based detectors [4].

References:

- [1] R. Wagner, J. M. Bradley and R. B. Hammond "Picosecond Photoconductors as Radiation Detectors", IEEE Trans. Nuclear Science, NS 33, #1, p.25 (1986).
- [2] Y. Shih, M. Hoinkis and E. R. Weber "A Study of Defects in Neutron-Irradiated GaAs" (to be published).
- [3] RD-42 Collaboration, "Recent Results from Diamond Microstrip Detectors", to be published in NIM-A (1995).
- [4] RD-42 Collaboration, "Radiation Hardness Studies of CVD Diamond Detectors", to be published in NIM-A (1995).

Fig.1. Periodic array of interdigital electrodes of alternating polarity to be used for current collection in LT GaAs-based radiation detectors (schematic).

Fig. 2. A schematic diagram of a diamond-based microstrip detector to demonstrate the feasibility for its use in high-luminosity colliders.

Fig. 3. Position resolution of a diamond microstrip detector.