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Development and characterization of a 3D GaAs X-ray detector for medical imaging

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ABSTRACT

Conventional semiconductor X-ray detectors for medical imaging have either a planar or a pixelated structure. The options available for detection materials are limited by the natural trade-off between the absorption of incident photons and the collection of free charge carriers with these two structures. This trade-off can be avoided by using az 3D structure, in which electrodes are drilled into the detector's volume. This article describes a prototype 3D semiconductor detector, using semi-insulating GaAs. A laser drilling technique was used to create electrodes in the volume of the material. The holes created were characterized by scanning electron microscopy. Electrode contacts were created using electroless Au deposition. The manufacturing process and the first gamma counting results obtained with ^{241}Am and ^{57}Co sources are presented. The system is capable of individual photon-counting without energy discrimination but requires further development to improve efficiency.

1. Introduction

Medical imaging systems, such as room temperature X-ray detectors in the 20–100 keV range, extensively use wide band gap semiconductor compounds [1]. Using a planar geometry, the photo-generated carriers must pass through the entire thickness of the detector in order to be collected by the electrodes. Due to the charge carrier transport properties of these materials, the allowable thickness for the sensor layer is limited, thus decreasing potential sensor sensitivity. This limitation could be overcome by using 3D geometry [2,3], where electrodes are drilled into the sensor's thickness. Charge carriers are transported perpendicular to the sensor thickness, as shown in Fig. 1. Most work relating to 3D detectors has been done on silicon sensors [4]. However, silicon is not ideal for X-ray detection in the 20–100 keV range as it has quite low absorption above 25 keV. SiC and GaAs 3D detectors have also been studied by Pellegrini et al. for high energy physic [5] and medical imaging [6] applications.

The goal of this study was to develop a prototype 3D-GaAs detector working in counting mode which could be used for digital radiography. For this specific application, typical X-ray tube voltage is 70 kV and the mean X-rays energy is 50 keV. We previously studied the geometry required for this type of detector by numerical simulation [7]. Main conclusion of this study was that, as using planar geometry, the charge carrier (electrons or holes) with the poorer transport properties limits the device performances, because both carrier types must reach the respective collecting electrodes. The optimal pitch between anodes and cathodes is thus set by the minimum mean drift distance of each charge carrier. This simulation was validated using a 3D semiconductor detector prototype using CdTe:Cl [8], which also served as a proof of concept for developing the 3D-structure. With the same geometry as in [8] with a 1 mm thick GaAs sensor could lead to 80% absorption efficiency at 50 keV, including 5% fill factor loss due to electrodes. The present article describes a 3D X-ray detector composed of semi-insulating (SI) GaAs. Furthermore, we aim to develop a sensor which could be an industrial product, that is why we have chosen to use readily available commercial SI-GaAs and conventional.

The semi-insulating GaAs samples are described in the first section; the hole drilling method using laser machining and its characterization are developed in the second section; and the final section details the characteristics of the device.

2. Manufacturing a 3D GaAs detector

2.1. Reasons for choosing GaAs

To select the most appropriate material for X-ray photon detection, we focused on three parameters: atomic number, resistivity and charge carrier mobility. Gallium arsenide, with its medium atomic number (31 for Ga and 33 for As), high resistivity (10^7 Ω cm for SI-GaAs) and high charge carrier mobility appeared

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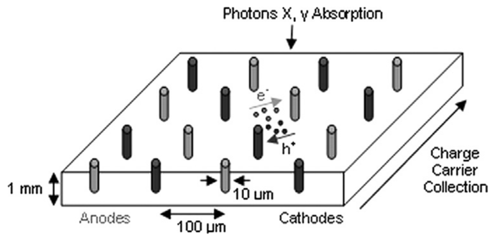

Fig. 1. Diagram of a 3D detector.

to be a good candidate. A 1.3 mm thickness of GaAs is necessary to stop 90% of X-rays at 50 keV.

Higher Z semi-conductor detectors (such as CdTe, HgI_2, PbI_2 or TlBr) were also candidates, but GaAs has several advantages over these despite its lower absorption efficiency. These advantages include its wide use in optoelectronic and high-frequency components and its availability as wide surface sections (up to 8″ wafers), which reduces costs. The processing technologies for GaAs have also been extensively developed. However, the lifetime of both electrons and holes in GaAs is very low, probably due to EL2 defects [9], which limit the allowable sensor thickness for an acceptable charge collection efficiency. Several solutions have been proposed to solve this, including chrome doping [10] or the use of thick epitaxial layers [11,12].

For this study, we wished to use readily available materials, we therefore chose SI-GaAs samples from Freiberger (Germany) grown by the Vertical Gradient Freeze (VGF) method. Good spectrometric performances have been obtained using SI-GaAs in previous studies [13], and a 200 μm thick GaAs sensor bonded to a Medipix ASIC [15] has been used for X-ray computing tomography in counting mode [14].

2.2. Hole drilling

In our prototype detector, it was necessary to drill high aspect ratio holes though the whole thickness of the sample. Several hole drilling techniques were available to us.

Deep Reactive Ion Etching (DRIE) is commonly used to drill semiconductors in the microelectronic and optoelectronic industries. DRIE is highly material dependent, as the chemical species chosen for etching must be selective. Its main advantage is that it allows a large number of holes to be made in a single etch. To create deep holes with straight edges, etching and passivation phases could be alternated (Bosch process). This has previously been done to create 300-μm holes with a 20:1 aspect ratio in a silicon support [16]. However, inductively coupled plasma etching (ICP) [17,18] may be a better option for creating deep holes in GaAs, although this technique has not yet proven to be suitable for creating holes deeper than 200 μm with a high aspect ratio. Other possible techniques include laser drilling, which is material-independent, but is a serial process. Laser-machining in combination with a plasma etch for damage removal has proved to produce an array of holes with an aspect ratio of 100:1 in a 1 mm thick silicon substrate [19]. Previously, we successfully used laser drilling in our laboratory to create a large number of holes with high (50:1) aspect ratio (diameter 20 μm, thickness 1 mm) in cadmium–telluride [8]. For this reason, we chose to use laser drilling to create holes in GaAs in this study. Unfortunately, alternating laser drilling and etch steps was not possible using our set-up. A pulsed laser was used in percussion mode, as detailed in Table 1. The drilling rate was assessed by measuring the hole depth with respect to the number of laser pulses, and was found to be 2.7 μm/shot in the conditions studied.

Table 1
Characteristics of the laser used to drill holes.

Type	Pulsed Nd-YLF
Mode	Percussion in air
Wavelength	263 nm
Pulse energy	600 μJ
Rate	3 kHz
Pulse width	40 ns
Time to drill a single hole	500 ms

Table 2
Characteristics of the two sample batches.

	Batch 1	**Batch 2**
Objective	Drilling characterization	Device characterization
SI-GaAs	VGF from Freiberger	VGF from Freiberger
Thickness	400 μm	600 μm
Pattern	3×3 holes matrix	3×3 holes matrix
Holes diameter	Entrance 80 μm, exit 20 μm	Entrance 120 μm, exit 50 μm
Holes pitch	350 μm	150 μm

2.3. Sample description

This study was focused to a single detection cell, with 3×3 holes, although our ultimate goal is to produce a large-area sensor. Two batches of detection cells were drilled, the characteristics of which are shown in Table 2. The first batch was used to tune the laser drilling technique and to check for laser-induced defects. The second batch had wider holes, to simplify bonding, and reduced pitch between holes, to reduce the mean drift distance for charge carriers. The charge carrier mean free path at operation voltage in this material is unknown because the charge carrier life-time has not been measured. This batch was used to manufacture a device. The thickness of the used supports enables an effective absorption of 40 keV photons, but is too thin to provide good quantum efficiency at higher energies. This must be considered as a first step before the thicker samples can be tested.

A sample from batch 1 was polished in the direction of slice for observation using a scanning electron microscope (SEM) (Hitachi 4100) (Fig. 2a). The holes showed good reproducibly but had a tapered shape, especially over the first 200 μm, with an entry diameter of 80 μm and an exit diameter of 20 μm. This tapering could be due to the shape of the laser beam or to absorption of the laser by ablated matter. Changing the laser power or the number of shots does not correct the tapering effect.

The large entrance hole diameter limits the minimum pitch and reduces the efficiency of the device, at least up to the depth where the holes become smaller. For thicker GaAs devices, (up to 1.3 mm as mentioned in Section 2.1), the process described in [8] could be used. For this study and as a first step, we have chosen to drill larger holes in order to limit the bonding difficulties. Optionally, considering that the tapering is mainly located on the entrance face, a thick sacrificial layer could be used on the entrance surface, and removed after the drilling process.

The surface of the holes also displayed micro-cracks (Fig. 2b and c). We attempted to remove these cracks on several GaAs samples by chemical etching with a sulphuric acid–phosphoric acid mix or citric acids. In all cases the cracks were exacerbated by further chemical etching.

Laser drilling with nanoseconds shots is a thermal process, therefore giving rise to a thermally and possibly chemically affected area around holes. To analyse such degradations, SEM images with topographical contrast (Secondary Electron mode) and chemical contrast (Back Scattered Electron mode) were