Use of Silicon Detectors in Medical Physics

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Abstract. In this document I will review the characteristics and applications of silicon detectors in Medical Physics. I will cover the activities done by some research mexican groups working with silicon detectors (Silicon Strip and PIN detectors) as devices for digital imaging supported by some Monte Carlo simulations and X-ray units parameters valuation devices for quality control. In the end I will give some perspectives on the future of these scientific activities as important contributions in the development of the area of Medical Physics around the world.

INTRODUCTION

As we know radiation is invisible to us, it cannot be smelled, touched, seen and nevertheless it can be harmful. It was necessary the study of the properties of the radiation to, in some way, have control on it and indeed apply it for our own benefit. The way radiation can be identified is through devices which can react when it passes through them. Some processes can take place when radiation interacts with matter: ionization if a charged radiation hit the material, or the well known effect as photoelectric effect, pair production, compton scattering, bremsstrahlung, if the radiation is uncharged.

The development of radiation detectors has passed for several periods, from identifying a single sound (Geiger-Muller), to the ability of localizing the position incidence (wire chambers, silicon detectors). Before 1950 Geiger counters, photographic emulsions and Wilson’s cloud chamber were the major detection instruments used; after that the bubble chamber took over much of the task. In the early sixties the spark chamber entered and evolved to the proportional wire chamber. Nowadays there exist several kind of detectors whose development depended on the application. There are ionizing chambers, proportional counters, scintillation material coupled with photomultiplier tubes, cerenkov and semiconductor detectors.

The principle of many detectors is the detection of a track left by the passage of a charged particle. When it passes through matter, it knocks out electrons from the atoms, thereby disturbing the structure of the material and also creating loose electrons. Thus a charged particle passed through matter leaves a trace of disturbed matter and move electrons from their positions that can be further collected. They can also detect uncharged radiation causing the effects mentioned above. We will see now more details of semiconductor detectors.
TABLE 1. Properties of silicon and germanium.

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Ge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>14</td>
<td>32</td>
</tr>
<tr>
<td>A</td>
<td>28.09</td>
<td>72.60</td>
</tr>
<tr>
<td>Density (300 K), g/cm³</td>
<td>2.33</td>
<td>5.33</td>
</tr>
<tr>
<td>Atoms/cm³</td>
<td>4.96 x 10²²</td>
<td>4.41 x 10²²</td>
</tr>
<tr>
<td>εᵣ (300 K), eV</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>Eₜ (300 K), eV</td>
<td>1.115</td>
<td>0.665</td>
</tr>
<tr>
<td>Intrinsic carriers density (300 K), cm⁻³</td>
<td>1.5 x 10¹⁰</td>
<td>2.4 x 10¹³</td>
</tr>
<tr>
<td>Intrinsic resistivity (300 K), Ωcm</td>
<td>2.3 x 10⁵</td>
<td>47</td>
</tr>
<tr>
<td>μₑ (300 K), cm²/Vs</td>
<td>1350</td>
<td>3900</td>
</tr>
<tr>
<td>μₜ (300 K), cm²/Vs</td>
<td>480</td>
<td>1900</td>
</tr>
</tbody>
</table>

SEMICONDUCTORS

Nowadays it is difficult to find a field where semiconductors have not been applied to improve systems of any kind. They are the core of computing development as integrated circuits have more capabilities. It is known that one of the greatest development in technology which influences life in our society was the invention of transistor, made of semiconductor materials as silicon and germanium (see table 1). The transistor (transfer resistor), was invented by a research team at Bell Laboratories in 1947. It has had an unprecedented impact on the electronic industry in general and on solid-state research in particular. Prior to 1947 semiconductors were only used as thermistors, photodiodes, and rectifiers. In 1948 John Bardeen and Walter Brattain announced the development of the point-contact transistor [1]. In the following year William Shockley’s classic paper on junction diodes and transistors was published [2].

The basic idea of a diode or transistor is the following: When p⁺ and n⁺ materials are put together there will be a junction where a depletion zone is created as well as an electric field. Then, the electrons and holes present in both materials undergo a net migration. This effect is called the drift velocity of the carriers. This migration or velocity depends on the electric field. Applying an inverse voltage this depletion region expands, decreasing the production of charges called leakage current. This low leakage current will be a basic feature for the application of semiconductor detectors in many areas.

Another application of semiconductors detectors is in high energy physic experiments, more particular in the detection of charged particles, products of the collisions of nucleons or heavy ions in the accelerators of international laboratories. Semiconductor detectors were mainly developed to identify the path of charged particles. The dominant advantage of semiconductor detectors lies in the smallness of the ionization energy. In particular detectors made of silicon, which it will be referred as silicon detectors, require only a charged particle energy of 3.6 eV to create an electron-hole pair while for a gas-filled detectors a 30 eV is needed. Thus it is expected that silicon detectors of-
fer better energy resolution and, depending on the design, good spatial resolution as well.

### SILICON DETECTORS

In general the principle of particle detectors is the identification of the tracks left by the passage of a charged particle by ionization. This interaction leaves a trace of disturbed matter and move the electrons from the original atoms to some terminals (wires, anodes) where they can be collected. This collected charge will be the signal that the rest of the electronic chain in the system will identify as the electronic pulse, it means, the signal.

As it was indicated the spatial resolution of the silicon detector depends on the design. Due to the great energy and spatial resolution and the small amount of radiation energy to generated an interaction in them, these detectors have been successfully applied in tracking and identification systems. There are pixel or strip detectors, two and one dimensional respectively. There are others which also identify the kind of particle through the energy deposited in it. Their energy resolution depends on the number of interactions on the detector. So in order to have a good energy resolution it is necessary to increase the number of information carriers creating during the interaction. The amount of charge deposited in the typical 300 μm of thickness of a silicon detector is around 25,000 electrons. Moreover the time required to collect the charge could be of nanoseconds, which makes them one of the fastest-responding of all radiation detector types. One can see in Fig. 1 a charged particle or photon hitting the detector ionizing it. Therefore, they are generally situated in the closest position of the particle interaction point of a complete detector experiment on elementary particle.

The main characteristics of the silicon detectors that make them useful devices are:

- Speed of reaction when radiation cross the surface of 10 ns.
- Spatial resolution \( \sim 10 \mu \text{m} \).
- Flexibility of design.
- Small amount of material (0.003 \( X_0 \) for 300 μm thick detector).
- Linearity of the response vs. the deposited energy.

![FIGURE 1. Charge particle and a photon hitting a silicon detector.](image-url)
Good resolution in the deposited energy.
Tolerance to high radiation doses.

A silicon detector can be visualized as a diode. Therefore it needs an inverse voltage to have a big depletion region, in general, as big as the detector is wide. This let the region ready for detecting radiation that will originate charges when crossing the wafer surface. The electric field created guides the generated charge to the cathodes. These cathodes are the $p^+$ material which collect the charge that will be transmitted to the electronics. For our detector these cathodes are the microstrips. Above each cathode there is a metallic cover to permit the connection between the detector and readout electronics via microboundings.

SILICON DETECTORS IN MEDICAL PHYSICS

In the last decades silicon detectors have entered to help in the development of the area of medical physics, in particular in digital imaging for diagnostic. Some of the most important characteristics of silicon detectors for Medical Physics are its good energy and spatial resolution and great signal-to-noise ratio.

A large part of medical images falls in the X-ray energy range of about 20-30 keV, where tissues and bones or calcifications can absorb enough radiation to be noticed in a radiological image. Silicon detectors have the possibility of detecting X-ray of this order of energy (see Fig. 2). As the size of these objects is fairly large (of the order of tenths of microns), silicon detector seem to be the proper candidate to be used for medical imaging.

![Efficiency of a Silicon wafer for different thicknesses](image)

**FIGURE 2.** Efficiency of a Silicon wafer for different thicknesses
Silicon Strips Detectors (SSD)

As a brief historical tale one can say that, although their applications have flourished in initially unimagined ways, SSD were born of a specific scientific need in elementary particle physics experiments: to detect and study particles with "charm", it means, particles containing a charm quark. The precision needed to extrapolate the tracks in order to keep the different vertices in focus should be much less than the particle lifetime multiplied by the speed of light. So for charmed particles the required precision is a few tens of microns, a value well within the capabilities of SSD [3].

Microstrip detectors provide therefore the measurement of one coordinate of the particle’s crossing point with high precision. Using very low noise readout electronics, the measurement of the centroid of the signal over more than one strip further improves the precision. Clearly the precision of this procedure depends on the noise of the readout chain (including the quantization error introduced by the analog-to-digital converter, which is important when using small signals). If digital readout is used (strip hit or not hit), the resolution is simply \[ \sigma = \frac{pitch}{\sqrt{12}} \] [4]. Figure 3 shows a detail of a SSD.

As was mentioned one of the fields that SSD are being applied is in the area of imaging, which means, using these devices to obtain digital images with a great spatial resolution. Digital images present some advantages when comparing to the conventional ones. Digital images have higher range of contrast efficiency with respect to conventional screen-film, also digital technology has the advantage to process the images in order to improve them, they can be transferred in a digital way, there is no more film development, avoiding retakes if the develop process is not well done, as others. In this sense it is promising that SSD be useful in mammography where the earlier the diagnostic of the presence of cancer is identified, the chances of saving lives increase.

FIGURE 3. Detail of a corner of a SDD
It is known that mammography is the best method for breast cancer diagnosis. One signal of the presence of cancer is the identification of microcalcifications in breasts. Mammography refers to obtaining radiographic images and identifying ill tissues in the zone. One of the issues that can help to get a better diagnosis of cancer is having good spatial resolution radiographic images. It is clear the interest of some research groups in the world to study the possibilities to apply SSD to get better digital images for helping doctors to give a better diagnosis. We will not enter into many details on breast cancer because it is not the scope of this document, but it is fair to say that these kind of researches are of great importance. Breast cancer is the second cause of death by cancer in the world. So the efforts to get better and earlier diagnosis to prevent this cancer will be in benefit for all.

At this point I will mention the contribution that my research group is doing in the Physic Department at Cinvestav. We are working with a SSD for imaging purposes. This SSD was part of a set of prototypes for the tracking system for ALICE detector at CERN [5]. The group responsible for this system was using the SSD also for imaging and, as we were participating with them for ALICE, we were given a SSD prototype to develop our contribution in Mexico. Thus, since 2001 we have made improvements in the idea of obtaining better images using the SSD with X-rays [6].

During the development of this research we have found some limitations to get good images and every time we go further solving them. For instance one of the limitations in using silicon strip detectors is that in the interesting energy range for diagnostic (10-50keV), the absorption length of silicon is of the order of mm, then only a fraction of the X-rays are converted in the commonly used 300 microns thick detectors. Therefore there are two limits in applying these devices to low energy range: the upper energy limit caused by the reduction of efficiency and the degradation of the intrinsic spatial resolution due to Compton scattering. The last limit is comparable or larger than the effect of diffusion during the transport of the signal charge to the read-out chain.

To avoid this limit, one idea is to use a SSD in the edge-on configuration, it means, letting the X-rays passing through the sample and hit the detector by one of its edge perpendicular to the strips. This can be seen as a very narrow and long detector, but the radiation has to travel centimeters in the silicon bulk before leaving it, increasing the probability of interaction.

Some techniques have been developed to improve the process of getting better contrast images, one of them is using dual energy substraction, as it was applied by this research group [7]. It is shown in Fig. 4 a picture of the SSD coupled with two readout chip.

There are other efforts for applying this prototype in anygography. So far there have been computing simulations to test the expected resolution to be reached. In reference [8] it is explained how these tests were performed using two different Monte Carlo softwares.
PIN detectors

During the last decade much effort has been dedicated to the research of amorphous silicon PIN diodes for application as radiation detectors, imaging generation in medicine as others. These detectors offer some advantages as low cost, high stability to radiation damage and the possibility to grow large active areas. These devices can also be integrated together with read-out circuits [9].

Among possible medical applications, amorphous PIN diodes are studied as X-ray detectors, to substitute normal screens with multiple advantages. Indirect detection, previously converting through scintillate screens the X-rays to visible radiation which is detected by the PIN diodes acting as photodetectors, has already been achieved [10]. Direct detection requires much thicker layers, which is difficult to get with the required stability and quality.

One group created and used PIN diodes developed at Electric Engineering Department in Cinvestav to valuate some parameters for quality control of X-ray units. The exposed a PIN diode to X-ray single shot to measure the exposure time, high voltage applied, and dose [11]. Nowadays there are still some efforts for applying these PIN detectors in imaging.

PERSPECTIVES

High contrast digital X-ray radiography needs advances in readout electronics, solid-state coupled to it and direct image capture. Great improvements in both the quality of the X-ray systems and in the photographic films have resulted in better image quality,

FIGURE 4. SSD with two readout chips.
which is essential for the doctors to assess and to diagnose the problems of the patients. However there is still room for improvements, particularly with regard to the dose needed to produce an image and to the reduction to the inevitable noise, which is the main limiting factor in revealing low contrast objects. The application of SSD can accomplish these necessities.

For SSD there are some international collaborations to continue the application of these detectors to imaging. There have been bilateral projects between this mexican group with some other international groups for instance cuban, italian, polish, colombian. Moreover there was an ALFA project which put together several research group to develop a digital system using SSD. This ALFA project was supported by the european community and the participant institutions. In this sense Mexico is participating and will continue being part of this research. We know in our country as well as in the world death for breast cancer is increasing. Any research which is addressed to find methods to discover earlier the possible presence of cancer in breast will be very well appreciated.

However, although digital mammographic units are available in the market nowadays and the need of having a direct digital imaging system, there are some other things to be improved. The things are for instance protocols for the physicians to valuated those digital images to get a diagnosis. Also it seems to be problems in the storage of big amount of data, cause every image requires at least tenths of Mb. The quality control of the X-ray units that use digital systems are not well established too. So, for our interests, we are working in solving and contribute to the improvement of the images taking into account the advantages that digital technology offers. The other details mentioned have to be solve in the near future because the step in changing from conventional to digital mammography is inevitable. We are contributing directly to this scope.

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