Application of PIN diodes in Physics Research

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Abstract. A review of the application of PIN diodes as radiation detectors in different fields of Physics research is presented. The development and research in semiconductor technology, the use of PIN diodes in particle counting, X-and γ-ray spectroscopy, medical applications and charged particle spectroscopy are considered. Emphasis is made in the activities realized in the different research and development Mexican institutions dealing with this kind of radiation detectors.

Keywords: PIN diodes, X-rays, spectroscopy, charged particles.

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INTRODUCTION

Whereas the concept of PIN diodes is very old, it was mentioned in a paper [1] by Kleinman in 1956, its application to radiation detection is more or less recent; for example, Nowotny and Reiter [2] reported low energy photon measurements in 1977. Since the proposal of the basic silicon point contact diode by Pickard in 1946 and its application in radar technology [3], the need to have faster devices surely lead the researchers to the PIN diode concept in which less capacitance and less reverse current provided better characteristics. As any semiconductor diode, PIN diodes are very sensitive to light, thus they are widely used for light detection mainly in communications through optical fiber lines, taking advantage of its fast response, PIN diodes are used at frequencies of 50 MHz or more [4].

In this review article we describe the main applications of PIN diodes as radiation detectors in different fields of Physic research in Mexico, covering some aspects of the work realized in semiconductors technology for producing PIN diodes, nuclear counting experiments, measurement of intensity of X-ray beams, energy spectroscopy of γ-and X-rays and charged particles. These activities have led to useful practical applications in medicine, industry and basic research. Beside this description, the main applications worldwide are also mentioned including the more relevant bibliographic references.

PIN DIODE DETECTORS

The basic structure of a PIN diode is seen in Figure 1(a); the three regions, n⁺, Intrinsic and p⁺, are shown. Figure 1(b) shows the picture of a commercial PIN diode.
Measurement of the radiation is based in the production of electron-hole pairs in the interaction of radiation with the detector material and the further collection of charges. There are two possibilities to operate the PIN diodes [5]: in photovoltaic mode without any bias voltage applied and in photoconductive mode with a reverse bias voltage applied to create a depletion zone inside the intrinsic region.

In Figure 2.a, the diode is in photovoltaic mode, the radiation is measured as an integral effect, a current is generated from the interaction of radiation with the detector, and the response is the average of the events inside the detector. This configuration is used in applications of photometry and to measure the intensity [6] of X-rays in radio diagnostic [7], the preamplifier converts the current to voltage, and the output signal has the waveform of the X-rays that reaches the detector, therefore it can be displayed in an oscilloscope.

In Figure 2.b, the diode is connected in photoconductive mode, the radiation is measured in every single interaction, a charge is generated due to the interaction of radiation with the detector and it is directly proportional to the energy of the radiation, the preamplifier converts the input charge to voltage. With this configuration, spectrometric measurements can be done [8]. PIN diode detectors need to be operated with enough reverse voltage in order to reach the maximum depletion zone and therefore to get the best detection efficiency.
The intrinsic detection efficiency is around 100% for photons of a few keV, and decreases to around 2% at 60 keV for a 300 µm thick PIN diode. The efficiency is around 100% for charged particles of moderate energy.

The electrical characteristics that are more related with the performance of PIN diodes as radiation detectors are the leakage current and the diode capacitance. Thanks to the good quality of silicon, the leakage current can be less than 100 pA at depletion voltage and the capacitance less than 2 pF for small diodes, therefore the PIN diodes can be used at room temperature with good performance for X-ray spectroscopy, but require a low input capacitance and low noise preamplifier as read-out circuit. Due to the very small signal generated in the detector for X-rays, the noise of the measuring system has to be considered with great care in this case.

**CHARGE SENSITIVE PREAMPLIFIERS**

The matching between the detector and preamplifier defines the low noise of the spectroscopy system, therefore for these applications; the best noise performance of the associated preamplifier is required. Generally, a field effect transistor, FET, is used as the input device. Special low noise preamplifiers have been developed to fulfill this requirement like the charge sensitive preamplifier that uses a feedback resistor, see Figure 2.b, in this case, the feedback capacitor is charged by the injected signal from the detector and discharged immediately through the feedback resistor. The feedback resistor has the disadvantage that it is an additional and undesired source of noise.

The charge sensitive preamplifier with optical feedback [9] is another possibility that do not include an additional source of noise by a feedback resistor. The feedback capacitor is discharged through the input FET, when an optically coupled LED sends a reset light pulse to the FET every time the output voltage, reaches a defined level.

**ENERGY SPECTROSCOPY OF RADIATION**

In a basic energy spectroscopy system, the signal of charge generated in the detector by the radiation is conditioned in a preamplifier, a spectroscopy amplifier gives a further amplification and sets the optimal bandwidth of the system in order to get the best signal to noise ratio, the output from the amplifier is a series of analog pulses with a height directly proportional to the energy of the detected radiation, these pulses are analyzed considering its pulse height, classified an the result of this classification is shown in the screen of a multichannel analyzer system.

The total noise of the system is reflected on the spectrum in the width of the peaks, the energy resolution of the spectroscopy system is defined [10] as the Full Width at Half Maximum of a peak, FWHM, for example, the resolution for X-ray detectors is measured in the peak of 5.89 keV of an Fe-55 radiation source.

The total noise is the resultant of two uncorrelated components: the electronic noise associated mainly with the preamplifier and the electrical characteristics of the detector; and the statistical component due to the detection process inside the detector [9].
RESEARCH AND APPLICATION OF PIN DIODES

Semiconductor Technology of PIN Diodes

The research on semiconductor technology to produce PIN diodes started in Mexico in 1996 with the project: “Radiation Semiconductor Detectors” [11][12][13][14][15][16][17][18][19][20] financed by CONACYT1 with the collaboration of several institutions as CINVESTAV2, INAOE3, ININ4 and CEADEN5. A second project started in 1999: “Semiconductor Structures for Radiation Detectors” [21][22][23][24] with the participation of the same institutions that continued with research on crystalline and amorphous silicon PIN diodes and special preamplifiers [25][26][27][28][29][30]. Research continued to incorporate the amplifying device in the same chip with the PIN detector on high resistivity silicon [31][32][33][34][35][36][37].

Since 1996, several Italian groups have made a big effort in research on semiconductor technology to optimize PIN diodes as radiation detectors, also they have worked in the integration of detector and the amplification device to produce arrays for the application of PIN diodes in image generation [38][39][40][41][42][43].

Applications in Medicine

PIN diodes have been used to measure the intensity of X-ray beams provided by Radiographic X-ray units in order to evaluate the main operational parameters related with the quality of the final photographic image in the film [44][45][46][47][48][49][50], such parameters are: the applied high voltage; the waveform of the high voltage, see Figure 3; the beam current; the exposure time and the applied dose, see Figure 4.

![Oscilloscope screens of X-ray beams measured with an X-ray waveform tester made with a PIN diode. a) Half wave X-ray unit, b) High frequency X-ray unit.](image)

FIGURE 3. Oscilloscope screens of X-ray beams measured with an X-ray waveform tester made with a PIN diode. a) Half wave X-ray unit, b) High frequency X-ray unit.

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1 CONACYT, National Council of Science and Technology of México.
2 CINVESTAV, Research and Advanced Studies Center, México.
3 INAOE, National Institute for Astrophysics, Optics and Electronics, México.
4 ININ, National Institute for Nuclear Research, México.
5 CEADEN, Center for Applied Studies in the Development of Nuclear Energy, Cuba.
FIGURE 4. Normalized response of a waveform tester made with a PIN diode to an X-ray beam with different accelerating voltages, 100 mA, and comparison with the response of other instruments [48].

Thickness measurements of thin biological samples have been done with PIN diodes and an X-ray beam for medical applications with success [51].

The good light sensitivity of PIN diodes has been combined with scintillation radiation detectors to make position detectors in PET applications as proposed by Derenzo and Moses in 1989 [52], in this way digital images can be generated. The direct detection of radiation in image applications also has been studied [53][54], in this case the PIN diodes are used as pixel elements.

Personal monitors for radiation protection and dosimetry have been done with PIN diodes and an appropriate build-up material that is selected according with the nature of the radiation to be detected, X-and γ-rays or neutrons [55][56][57].

**Photon Spectroscopy**

Si-Li detectors are normally used to get the best results in X-ray analysis due to its good energy resolution, typically 180 eV, and good efficiency in the energy range from 1 keV to 100 keV, nevertheless there are special PIN diodes [58] commercially available and suitable for X-ray detection, these detectors have some nice advantages over the Si-Li detectors mainly regarding the size and compactness. We demonstrated the detection capability of an OPF420 PIN photo diode [8], in this application. The employed preamplifier configuration was the forward biased FET charge amplifier, FBFA [59][60], in order to get the minimum noise. The FBFA configuration is shown in the Figure 5, \( C_f \) is discharged through the input field effect transistor biased with the gate in forward mode [9]. The obtained characteristics of the proposed system at room temperature are: conversion gain 22 mV/fC, with a feedback capacitance of 0.045 pF; the equivalent noise referred to the input is 20 electrons (rms) with an amplifier shaping time of 1.5 µs; the resolution of the system for an Fe-55 source is 1.02 keV.
The spectrum for an Am-241 source obtained with the PIN diode is compared with the one obtained with a Si-Li detector, as shown in Figure 6. In this figure a good correspondence of the peaks position in both detectors is observed, which guaranties the good linearity of the PIN diode experimental results. Similar results are reported in the literature [61][62]. This system has been used with success in different experiments at ININ [63].

In the Plasma Focus experiment at UNAM\textsuperscript{6}, PIN diodes are used to measure soft X-rays produced at the experiment and to make diagnostic of the conditions in the generated plasma [64].

Generally, $\gamma$-ray spectroscopy with PIN diodes is performed by indirect measurement of radiation employing different scintillation detectors [65].

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Charged Particle Spectroscopy

The application of different planar silicon detectors to the detection of charged particles has been reported widely in the literature [66], [67], [68]. Specially devised PIN photodiodes have been reported for charged particle spectroscopy [69] and also for use in heavy ion collision experiments [70].

The research for PIN diode preamplifiers [71][72] started in Mexico in 1995, later on, we proposed [73] a PIN diode–preamplifier set that could substitute a silicon surface barrier detector, SSB, in some applications; for example, a spectrum from alpha sources such as \(^{239}\)Pu, \(^{241}\)Am and \(^{244}\)Cm is shown in Figure 7.a, it also has been applied in the measurement of charged particles in experiments at accelerators and in Rutherford backscattering analysis in the energy range of 4 to 13 MeV, see Figure 7.b. The electronic noise of the preamplifier, measured with a pulser, was less than 2.14 keV.

![Spectra obtained with the proposed PIN diode-preamplifier set: a) spectrum of calibration alpha sources; b) Rutherford backscattering spectrum for a thin layer.](image)

Energy loss measurements for different ions have been done by using PIN diodes and a stopping medium, thus, stopping forces have been measured accurately [74] which provided more information to ion beam analysis.

**Radiation Damage on Semiconductor Structures**

Damage from radiation has been observed in PIN diodes due to particle bombardment [73], the measurement of the increase in the leakage current and forward voltage, see Figure 8, which evidence the damage of the detector, can be used as a tool to evaluate the unknown total number of incident particles reaching the detector. The increase of the leakage current in the detector worsens drastically the noise behavior of the system [10].

Reinhard proved [75] that a PIN diode can be a good radiation damage monitor for mixed fields of electrons, fast and epithermal neutrons.
Spatial Applications

In spatial research the PIN diodes are been widely used as environmental monitors for mixed fields of high energy particles and gamma rays [76], only some examples are mentioned as follows: the Cosmic-Ray Effects and Activation Monitor (CREAM) experiment; Cosmic Particle Experiment (CPE); Total Dose Experiment (TDE); Cosmic-Ray Effects and Dosimetry (CREDO) payload. Under UoSAT-3 experiment in 1990 and in CEDEX\textsuperscript{7} at Surrey Space Center in 2000, PIN diodes have been used for the measurement of protons and heavy ions fluxes inside the spacecraft.

In 1997, under the Pathfinder mission, spectra of Martian rocks analyzed by X-ray fluorescence were sent to earth, the detector in this case was a cooled PIN diode [77], cooling was made by applying thermoelectric effect.

High Energy Physics, HEP, Applications

The use of PIN diodes in HEP big experiments is related mainly with the detection of charged particles. PIN diode Beam Loss Monitors (BLM) are employed commonly in: the European Synchrotron Radiation Facility[78], in HERA\textsuperscript{8} at DESY\textsuperscript{9} since 1987 [79]; at Tevatron of FNAL\textsuperscript{10} to measure the loss of protons and antiprotons in the beam since 1997 [80]; the Beta meson And Anti Beta meson experiment (Babar collaboration) to measure the background produced by the beam since 1997 [81]; and the RHIC\textsuperscript{11} [70] in the STAR\textsuperscript{12} experiment in 1999.

The PIN diodes were used as light detectors in digital optical links for fast data transmission in the tracker control system of the Compact Muon Solenoid (CMS) at CERN [82], and in the SCT\textsuperscript{13} and pixel detectors [83] at the ATLAS\textsuperscript{14} detector.

\textsuperscript{7} CEDEX, Cosmic Ray Energy Deposition Experiment
\textsuperscript{8} HERA, Hadron Electron Ring Accelerator
\textsuperscript{9} DESY, Deutsches Elektronen Synchrotron
\textsuperscript{10} FNAL, Fermi National Accelerator Laboratory, USA
\textsuperscript{11} RHIC, Relativistic Heavy Ion Collider at Brookhaven National Laboratory, U. S. A.
\textsuperscript{12} STAR, Semiconductor Tracker at RHIC.
\textsuperscript{13} SCT, Semiconductor Tracker.
\textsuperscript{14} ATLAS, A Toroidal Large Hadron Collider (LHC) Apparatus
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