High Efficiency Detection of Tritium Using Silicon Avalanche Photodiodes

K.S. Shah, P. Gothoskar, R. Farrell, and J. Gordon
RMD, Inc., 44 Hunt Street, Watertown, MA 02172

Abstract[1]

This paper describes our recent work in developing low noise silicon avalanche photodiodes (APD) for detection of tritium (^{3}H) β-particles with high efficiency. In view of the very low energy of ^{3}H β-particles (E_{max}=18 keV), research was carried out to produce APD structures with a very thin entrance window. This involved using low energy boron implantation into the APD front surface, followed by pulsed excimer laser annealing of the implanted face to form a p^+ contact. The resulting devices had surface dead layer of about 0.07 to 0.1 μm and operated with low noise threshold (250-300 eV) for 2x2 mm^2 size. The ^{3}H β-particle detection efficiency was measured to be approximately 50%. This is about the twice the detection efficiency achieved with standard APDs.

I. INTRODUCTION

Silicon avalanche photodiodes (APD) are attractive devices for detection of optical photons, low energy charged particles and X-rays. Due to the internal gain in these devices, the signal amplitude is higher than that in unity gain devices and this leads to higher signal to noise ratio in many applications. Furthermore, the internal gain and the resulting larger signal amplitude places less stringent requirements on the front-end electronics in low noise applications.

In the simplest form, an APD is a reverse bias p-n junction that is operated close to its break-down voltage. When photons or charged particles are absorbed in the semiconductor, the resulting electron-hole pairs are accelerated due to high applied electric field. These charges gain sufficient velocity to create free carriers by impact ionization, resulting in internal gain. At RMD we have been conducting extensive investigation of APD as optical and radiation detector using the basic design of Locker and Huth [1,2]. In this design, a beveled edge is used to reduce the electric field at edges. Figure 1 shows a schematic representation of a beveled edge APD design. As seen in the figure, the APD consists of several regions including the drift region, space charge region, and a thin multiplication region (not shown in Figure1). Free carriers are generated in the drift region which are swept to the space charge region. No external electric field is present here but a gentle dopant profile creates a small electric field to to move the charges to the multiplication region. Since the dopant concentration in the space charge region is low, the carrier lifetimes are quite large and the charges are efficiently transported to the multiplication region where they attain sufficient velocity to cause knock-on collisons with bound electrons and thereby create amplification or gain. APDs with gain exceeding 10,000 have been developed using this device design [3].

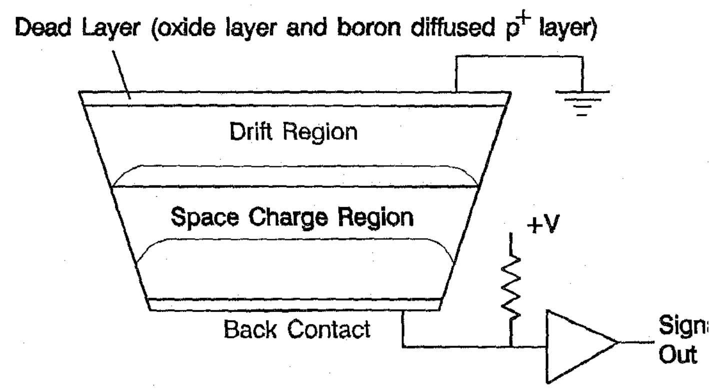

Figure 1. Schematic diagram of a beveled edge APD

Due to high gain in these devices, they are capable of providing high signal to noise ratio for detection of low energy X-rays as well as β-particles. This makes it possible to develop a solid state sensor for detection of tritium or ^{3}H β-particles (E_{max} = 18 keV) which are commonly used in radioactive labeling of proteins. While the signal to noise ratio in standard APDs is low enough for ^{3}H detection, these devices have a relatively thick (0.3 μm) dead layer on the surface (mostly due to p^+ contact). The tritium detection efficiency of the standard APDs is about 26%, which is considerably lower than that of liquid scintillation counters (65%) that are used in tritium radiolabeled studies. In this paper, we report on a new p^+ front electrode preparation which has lead to a significant increase in tritium detection efficiency of the APDs.

II. FRONT ELECTRODE FABRICATION:

Traditional front p^+ contacts are fabricated by diffusing boron into the APD front surface at high temperature. This results in high concentration of free carriers in the surface layer which acts as the entrance electrode. The devices fabricated with such contacts operate with very low noise (200-400 eV threshold for 4 mm^2 area, where the threshold is measured at background count-rate of 3 counts/sec and

[1] Support for this work was provided by the NIH grant # 2R44MH53694-02.

0018-9499/97$10.00

corresponds roughly to twice the FWHM of an injected test pulse). However, due to high temperatures required in this fabrication step, the boron atoms diffuse significantly in silicon and the typical contact thickness is 0.2-0.3 μm. While this thickness is small enough to obtain efficient detection of low energy X-rays and high energy β-particles, the ^3H β-particles have very small absorption depth in silicon (≈0.15 μm). As a result, the standard APDs do not have very high tritium detection efficiency (23-26%).

In view of this, we have experimented with a new approach to fabricate thinner p^+ contacts (see Figure 2). This involved implanting boron into the APD surface with the boron ion energy adjusted to about 20 keV. The range of such ions in silicon is about 0.07 μm as estimated using TRIM89 [4]. This surface needs annealing in order to activate the implanted ions and to remove damage caused by implantation. Pulsed excimer laser annealing was used. for this purpose.

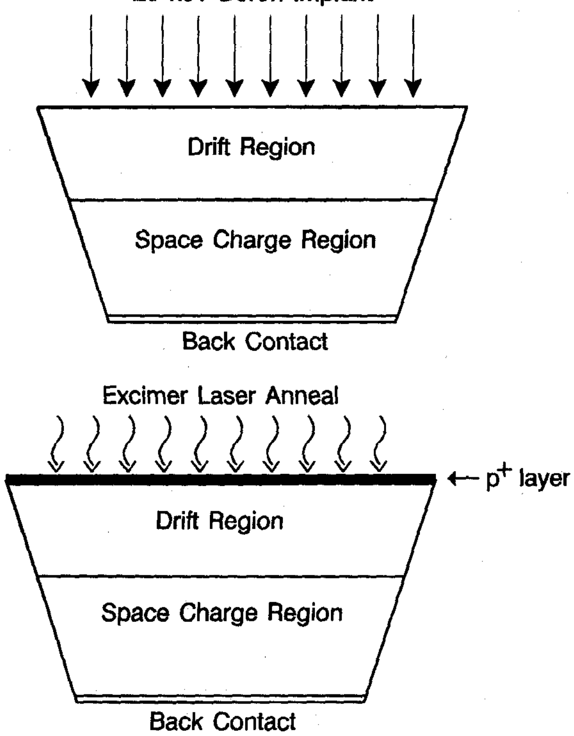

Figure 2. Ion implantation and laser annealing process to produce thin p^+ contacts on APDs.

The laser annealing process involves irradiating the implanted surface with a pulsed laser beam of adjustable energy. The laser energy is carefully controlled to melt a thin surface layer which covers the depth of the implanted region. The melted layer then regrows epitaxially on the single crystal substrate underneath and is relatively damage free [5]. Since the excimer lasers emit in the UV range, the laser light is absorbed very close to the surface (0.05-0.1 μm) and localized annealing occurs. Also, very short pulse duration (15-20 ns) of the laser prevents any redistribution of boron by diffusion effects and very thin junctions can be obtained.

During the annealing experiments, the silicon wafers were mounted on a Teflon holder and the implanted face was kept facing the laser beam, which was focused to form a 1 mm^2 image spot on the wafer. The spot was scanned across the entire wafer and the laser energy was varied between 0.5 to 3 J/cm^2. Sheet resistance of the resulting surface was measured to be 25 Ω/□. Devices (2x2 mm^2 area) were fabricated from such wafers and characterized.

III. Device Testing Results:

APDs fabriacted with modified surface preparation were first tested by measuring their dark leakage current and gain and the results were found to be comparable to standard APDs. These APDs were then characterized by measuring their noise, X-ray detection and ^3H detection efficiency. Figure 3 shows ^{55}Fe spectrum (5.9 keV X-rays) taken with an APD processed in the described manner. Also shown is a noise spectrum recorded without any source present. From the energy calibration obtained using 5.9 keV X-ray peak, the noise threshold was estimated to be about 250-300 eV, which is comparable to the standard devices of similar size. This result indicates that our new devices are capable of low noise operation. Also shown in Figure 3 is the ^3H β-particle spectrum. From the known source activity at the surface, and measured tritium counts above noise, we estimated the detection efficiency to be approximately 50%. This is about twice the efficiency of the standard APDs. Thus our new surface treatment has lead to higher ^3H detection efficiency.

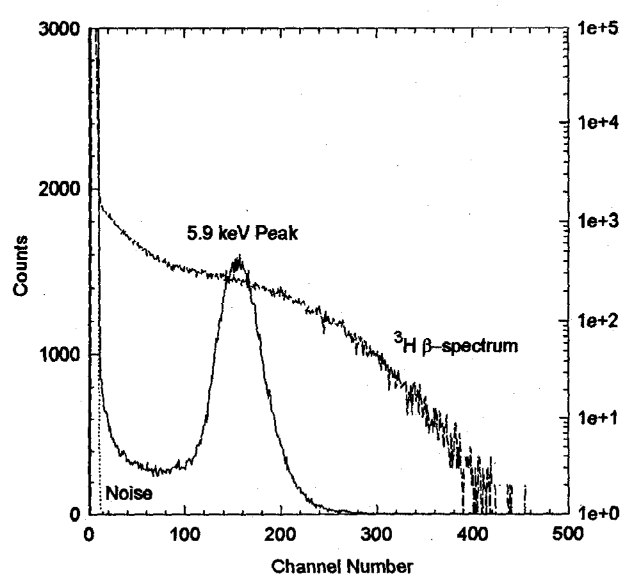

Figure 3. Noise, ^{55}Fe X-ray (5.9 keV), and ^3H β-particle spectra measured with the new APDs. The noise and the ^{55}Fe X-ray spectra are shown on a linear vertical scale (refer to the left Y-axis), while the ^3H spectra is shown with a logarithmic vertical scale (refer to the right Y-axis). The ^3H detection efficiency is estimated to be 50%, and the end point energy for the ^3H β-particles in the spectrum is about 15.5 keV. The noise threshold is about 250-300 eV.

The dark current was approximately 40 nA (for 2x2 mm^2 devices) while the gain was about 200 under operating conditions. The ^3H detection efficiency was found to be a function of laser pulse energy (see Figure 4), and at low pulse energy, the efficiency was poor due to insufficient annealing and dopant activation in the surface layer. Upon increasing the laser energy, the efficiency improved until the surface layer was completely regrown. When the energy was increased further, the surface appeared pitted indicating laser induced damage.

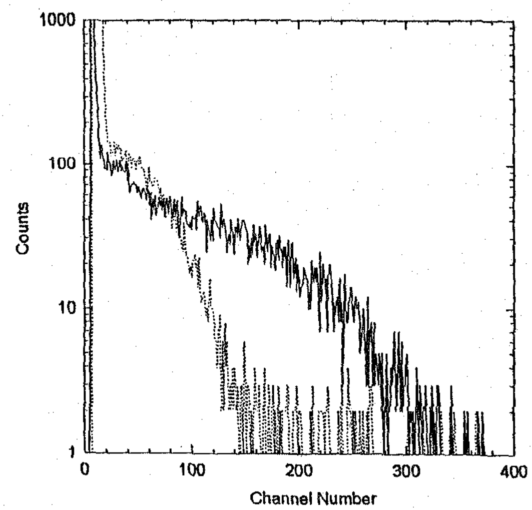

Figure 4. ^3H spectra for two different laser energies, the low amplitude spectrum being for laser energy less than the optimal one.

IV. SUMMARY:

A new surface treatment has been developed for preparing thin front contacts on APDs for enhancing their efficiency in detecting low energy beta particles. This treatment consisted of implanting boron on the front APD surface and then treating the implanted face with a pulsed laser beam to anneal the damage. This process has lead to doubling of ^3H detection efficiency as compared to the standard APD fabrication process. The ^3H detection efficiency is about 50% with the new technique.

V. REFERENCES

[1] G.C. Huth, IEEE Trans. Nuc. Sci., NS-13, page 36, 1966
[2] R.J. Locker and G.C. Huth, Appl. Phys. Lett., 9, page 227, 1966
[3] R. Farrell, K. Vanderpuye, L. Cirignano, M.R. Squillante and G. Emtine, Radiation Detection Performance of Very High Gain Avalanche Photodiodes, Nuc. Inst. & Meth., A353, page 176, 1994
[4] J. Zeigler, TRIM89-The Stopping and Range of Ions in Matter, V5.4, 1989
[5] J. Poate and J. Mayer, editors, laser Annealing of Semiconductors, Academic Press, 1985