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GaAs PHOTODIODES FOR HIGH-ENERGY PARTICLE DETECTORS

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Abstract

We have developed an original technology for production fast photodetectors, based on doped (compensated) $GaAs$ and sensitive in the 200 860 nm range. Using the production technology developed, laboratory-scale $1 \times 1cm^2$ photodetector prototypes were build. Stationary voltage-current characteristic, barrier capacitance as a function of bias as well as spectral dependence of the photodetector sensitivity evaluated.

1. INTRODUCTION

Scintillation particle detectors are the widespread devices used both in nuclear and high-energy physics. Scintillation light flashes are generally detected by means of photomultiplier tubes (PMT). While PMTs provide good performance for most of applications, they still suffer from certain defects, which limit their use. These defects are well known:

- high sensitivity PMT to magnetic fields,
- short linearity range,
- large dimensions,
- high cost.

Therefore already long ago works are carried out to create of semiconductor photodetectors, which would be might replace PMT in scintillation detectors and don't have enumerated limitations. This problem has become even more important in view of experiments on modern colliders. When used in calorimeters instead of PMTs the semiconductor photodetectors would significantly increase the linearity range of the devices and reduce their dimensions and, consequently, cost.

Emission spectra of most scintillators employed in high-energy physics exhibit peaks around 400-450 nm. Certain scintillators, for instance BaF_2 and liquid Xe, emit fast components in ultraviolet range of wavelengths. Conventional solid-state Ge and Si photodetectors are sensitive between 400 and 1000 nm, with spectral sensitivity peaking around 800 nm. The shift of the photodetectors sensitivity toward short-wave range requires the use of wide band-gap materials such as gallium arcenide and its isoelectronic analogs. The most promising trend in the development of high sensitivity photodetectors for the visible and ultraviolet regions of a spectrum is the use of high-resistance $GaAs$ diode structures.

An important advantage of high-resistance $GaAs$ diode structures over Si-based devices is a higher speed of response and radiation resistance. lower dark current and working voltage. The object of this work is the development and evaluation of characteristics of fast high-sensitivity large-area $GaAs$ photodetectors sensitive in the 200-1100 nm range.

2. $\pi - \nu - n$ type $GaAs$ PHOTODETECTOR PRODUCTION TECHNOLOGY

Properties of solid-state devices are mostly determined by dopes specially introduced in the semiconductor. It has been common practice to employ dopes inducing the formation of centers with low-lying energy levels that within the operating temperatures of the device are in ionized state. We have made use an unconventional approach. Semiconductor structures were formed in the course of doping by impurities creating centers with deep energy levels [1]. Deep centers are with this in unionized state and can be recharged subject to external actions. This provides extra degrees of freedom to control the instrument parameters. In the structures with deep centers some new physical effects have been discovered. in particular. high sensitivity to the ultraviolet [2.3].

In developing $GaAs$ photodetectors we proceeded from the following assumptions:

- $GaAs$ semiconductor structures exhibit enhanced radiation resistance:
- $GaAs$ as compared to Si a wider band gap and. importantly. a direct band gap semiconductor. which implies that. besides the direct radiative effect. the infrared radiation converted near the surface can be used. by that increasing the photosensitivity:
- physical processes that are unusual for conventional structures take place: long the minority-carriers life time in high-

resistance area of structure and presence of built-in fields stimulating a recharge of deep centers.

These assumptions have been used to develop several semiconductor structures. These include p-ν-n, p-π-ν-n, n-π-ν-n and p-ν- π-p types. Always the thickness of the surface p and n layers was 0.1-1.0 μ. Irrespective of the design used, the π-ν-n structure forms a basis for the photodetectors.

In the course of the development of the semiconductor production technology we have found that the photosensitivity, stability and reproducibility of the photodetectors are essentially dependent on the electro-physical parameters of the original $GaAs$. The latter should have lowest dislocation density possible and homogeneous doping level and crystalline defects. The dopes concentrated along the dislocations shunt high-resistance structures forming conductivity paths or stray capacitances.

We have developed a laboratory-scale $GaAs$ production technology using the method of horizontal directional crystallization (HDC) in magnetic field. It provides $GaAs$ with uniform electro-physical properties, low density of dislocations and high thermostability. The double zone method for simultaneous crystal synthesis and growth was adopted as a basis for GaAs production. This allowed for a simpler design of the crystal growth experiments, on the one hand, and a small change in the Ga and As ratio in the melt and crystals with a preferential stoichiometric shift toward the enrichment of $GaAs$ with arsenic, on the other. This change occurs due to temperature variation. Initial components used was 99.9997 % Ga and As, which provide an uncontrolled impurity level of $< 10^{17} cm^{-3}$. Magnetic field strength for the growth process was 1000 Oersteds. For 40 mm diameter quartz crucibles the monocrystal mass was 300 g. To avoid the adhesion of the growing crystal the internal surface of the crucible was subjected to sand blasting followed by gallium melt treatment at high temperatures.

The dislocation density in the crystals grown by the method of double zone in magnetic field is by an order of magnitude lower than that in the Czochralski-grown commercial crystals.

Laboratory-scale technology of the semiconductor photodetector production included simultaneous doping of thin GaAs wafers with acceptors having deep energy levels and donors having low-lying energy levels. The doping was performed under the high temperature diffusion and the liquid and the vapour-phase epitaxy. Evaluation of the results obtained shows that diffusion and liquid-phase epitaxy are preferable to vapour-phase epitaxy. Structures produced by these methods exhibit better photosensitivity.

3. MEASUREMENT of PHOTODETECTORS PARAMETERS.

In the course of the operational design and engineering development a few tens of mock-up prototype photodetectors ($2 \times 3mm^2$) have been constructed. The photodetectors differ in the initial $GaAs$ parameters and high-resistivity layer doping thickness and level. Spectral photosensitivity of the resulting structures was examined. and the best prototypes for time response and amplitude were selected. Using the production technology developed. laboratory-scale 1x1 cm^2 photodetector prototypes were build. and their stationary voltage-current characteristic. barrier capacitance as a function of frequency and bias as well as spectral dependence of the stationary photocurrent evaluated.

Typical voltage-current characteristic for the reverse bias is shown in Fig.1. It includes the following distinctive sections:

I. Linear dependance up to 0.1 V of the reverse bias.

II. Section with J = const(U) for (0.1-15) V. A complete depletion of the high resistivity layer occurs within the first portion of this section.

III. Exponential rise of current at $U > 15V$. This section corresponds to the development of the avalanche breakdown in the space charge region of the $p - n$ junction.

The sensitivity of the $\pi - \nu - n$ type structures increases as the high-resistivity layer thickness is decrease, while the capacitance grows higher. Optimal thickness is found (30 - 40)μ. Relevant calculated capacitance is 330 pF for a 1 cm^2 detector. Measured detector capacitance for 1 MHz is 240-320 pF.

Spectral characteristics of the photosensitivity of the semiconductor structures were studied using an experimental setup whose basic unit was MDR-3 monochromator. We used two different light sources in the experiment: an incandescent OPZZ-03 lamp for 0.4-1 μ and a DDS-30 deuterium discharge lamp for 0.2-0.6 μ. The lamp output was focused on the entrance slit of the monochromator, and the light from MDR-3 was passed to the photodiode in question. In the 0.6-1.1μ range we measured the spectral density of the monochromator light flux by a calibrated Si photodiode (FD-7K). At shorter wavelengths the spectral density was found from the PMT-100 photocurrent whose photosensitivity was between 0.2-0.8 μ. The photomultiplier was calibrated by a Si photodiode for overlapping wavelengths of 0.6-0.8 μ. The spectral photosensitivity was examined under photovoltaic conditions at invariable light flux. P. The measured values were the dark current J_d and short-circuit photocurrent J_p, which determined the current sensitivity S_i of the photodetector ($S_i = J_p - J_d/P$).

A typical spectral dependance of the photodetectors current sensitivity is shown in Fig.2. A peak sensitivity of 0.2 A/W was observed near the self-absorption edge. In the ultraviolet spectral region the photosensitivity varied from 0.005 to 0.1 A/W. Nonmonotonic behavior of the function is related to peculiarities of $GaAs$ reflection spectra.

Photosensitivity and detectability D of the photodetectors as the functions of bias were examined under photodiode conditions. The results presented in Fig. 3 show that in spite of the current photosensitivity rise, the detectability decreases with increasing bias that is due to the increase of the dark current. Photovoltaic mode is consequently the preferable one for the detection of the extremely weak light signals.

We measured the time response of the photodetector and evaluated its photosensitivity in a pulsed exposure mode. The experimental setup used included the light-emitting diode AL307 B as a light source operating in a breakdown regime at the reverse bias. Power to the light-emitting diode was applied from a TR-0306 mercury pulse generator with a pulse amplitude of 1 kV and duration of 4 ns. We used a fiber light guide to pass the light-emitting diode signal to the photodetector. Monitoring of the light pulse parameters and absolute calibration of the pulsed light source were performed by means of PMT-130.

The latter exhibits good one-electron characteristics, and its spectral photosensitivity overlaps the output spectrum of the light-emitting diode.

Light source calibration procedure consisted in the measurement of the PMT pulse amplitude as a function of the primary photoelectron number knocked out by the radiation from the PMT photocathode. The shape of the PMT pulse amplitude distribution was assumed to be virtually determined by fluctuations of the photoelectron number, while all the other fluctuation sources were regarded to be independent of the light intensity. The change from the photoelectron number knocked out from the PMT photocathode to the photon number was made on the basis of the PMT specifications and overlapping of the light-emitting diode output spectrum and spectral photosensitivity of the PMT cathode.

We have developed a fast preamplifier to measure the time response of the photodetectors. The preamplifier is based on integrated circuit M421104-2, i.e., a hybrid wive-band amplifier with a cutoff frequency of 700 MHz. Preamplifier has the following parameters:

- input and output resistance 50 Ohms,
- gain factor 10^4,
- bandwidth 0.1-500 MHz,
- output pulse $U < 0.5\ V$.

When the photodetector was exposed to charged particles the pulse duration at the output of the preamplifier was found 2 ns for the leading edge and 7 ns for the trailing edge. The photodetector sensitivity for pulsed exposure to the light-emitting diode output at 567 nm wavelength was 0.11 A/W, which differed but insignificantly from the measurements made at continuous exposure.

Thus, our photodetectors show high sensitivity in a broad range of wavelengths and can be readily used in detectors for high energy physics applications.

References

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Figure Captions

Fig. 1 Photodetector voltage-current characteristic at reverse bias.

Fig. 2 Spectral dependence photodetector current sensitivity.

Fig. 3 Detectivity and photosensitivity under photodiode conditions.

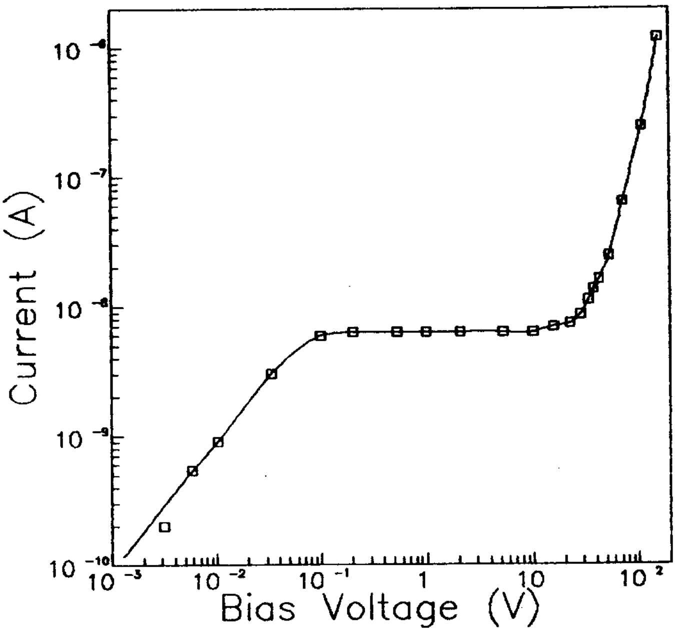

Fig. 1.

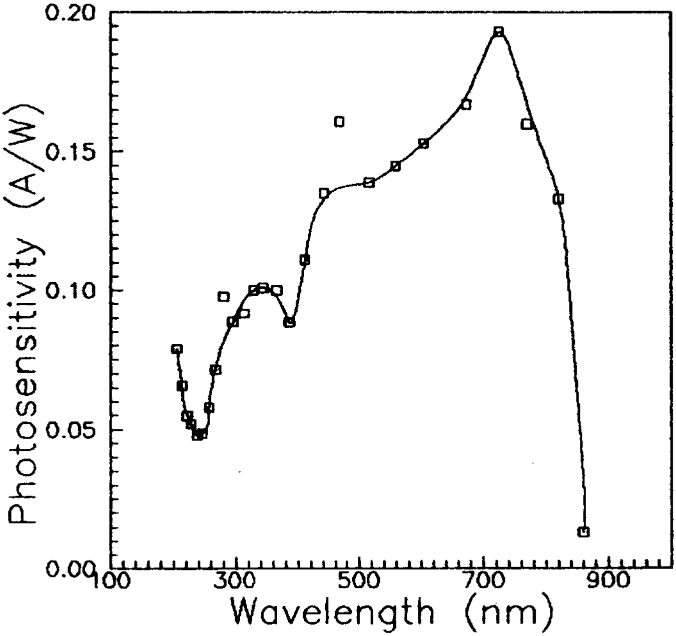
0.20
0.15
0.10
0.05
0.00
Photosensitivity (A/W)
100
300
500
700
900
Wavelength (nm)

Fig. 2.

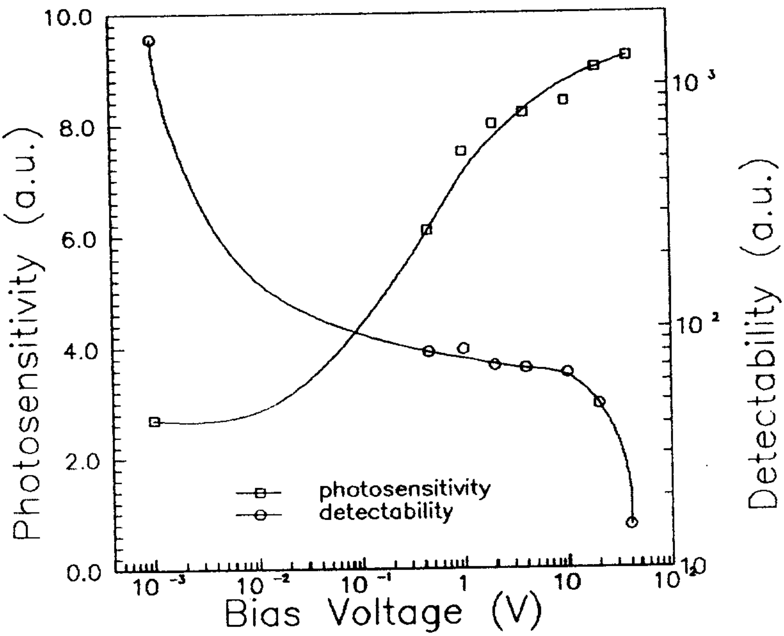
Photosensitivity (a.u.)
Detectability (a.u.)
Bias Voltage (V)
photosensitivity
detectability
10.0
8.0
6.0
4.0
2.0
0.0
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{2}
10

Fig. 3.