GRADED-GAP Al$_x$Ga$_{1-x}$As IONIZING RADIATION DETECTORS *

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Fabrication and measurements of the graded-gap Al$_x$Ga$_{1-x}$As ionizing radiation detectors are reviewed. Operating principles of the detectors with optical and electric response are discussed. High X-ray light internal conversion efficiency and X-ray image spatial resolution better than 15 lines/mm are obtained for detectors of square area $2 \times 3$ cm$^2$ with optical response. The main factor reducing the external conversion efficiency is high total internal reflection from the surface. Graded-gap electric field enables 100% generated charge collection in Al$_x$Ga$_{1-x}$As layer of thickness 27 µm without application of any external voltage. Due to this property, the graded-gap $p$-Al$_x$Ga$_{1-x}$As/n-GaAs structure can be used as a high-efficiency soft X-ray and single particles ($^{241}$Am alpha particles) detector operating without any bias. The new charge multiplication method, by increasing reverse current, was realized in the $p^+$-Al$_x$Ga$_{1-x}$As/n-GaAs graded-gap structures, in which the multiplication coefficient exceeded 200.

Keywords: radiation imaging, X-ray detector, graded-gap Al$_x$Ga$_{1-x}$As structures

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1. Introduction

Graded-gap epitaxial Al$_x$Ga$_{1-x}$As layers and multilayer structures are promising materials for detectors of ionizing radiation. The change of the Al fraction $x$ along the thickness of the layer causes change in the energy band structure which is responsible for specific properties of graded-gap Al$_x$Ga$_{1-x}$As layer [1]. The energy gap between the conduction and valence band increases from 1.42 to 1.9 eV with increasing $x$ in the interval $0 < x < 0.4$. The most important property of graded-gap structures is a wide-gap optical window for transmission without absorption of the emitted light in the crystal and the presence of an internal graded-gap electric field that can collect generated charge without application of any external voltage. Graded-gap Al$_x$Ga$_{1-x}$As structures can be used as ionizing radiation detectors operating either in optical or electric response mode.

2. Detectors with optical response

The detection of charge generated by ionizing radiation by using conversion of the charge to recom-


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hogeneous luminescence were fabricated. A schematic band structure of the detector with optical response is shown in Fig. 1.

The calculated dependence of the X-ray absorption coefficient $\alpha$ in the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layer on the photon energy $E_X$ of X-rays shows a large decrease of $\alpha$ with the increase of $E_X$ (see Fig. 2). The $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layer of $d = 100 \, \mu\text{m}$ absorbs up to 95% of the X-ray power at energies $E_X < 20 \, \text{keV}$. At $E_X > 50 \, \text{keV}$, the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layer with $d = 100 \, \mu\text{m}$ is transparent to X-rays. Therefore, the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layer of thickness 20–100 $\mu\text{m}$ can be used for detecting soft part of the X-ray spectra with energies less than 30 keV [3].

The experimental measurement of X-ray absorption in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layers was performed using an X-ray tube with a Cu anode. The X-ray intensity spectrum of this source is in the range of $3 \cdot 10^3 < E_X < 3 \cdot 10^4 \, \text{eV}$ at the anode voltage of 30 kV with maximum amplitude at $E_X \approx 8 \, \text{keV}$ [4]. The measured X-ray absorption coefficient $\alpha$ in this range of $E_X$ is shown in Fig. 2.

The optical image of X-ray intensity was detected by a charge-coupled-device (CCD) camera, and the data were read by a personal computer (PC), Fig. 3. Several other methods of optical response detection with a fibre line or a mirror system can be used. A Si photodiode or a CCD camera can serve as an optical signal receiver.

The efficiency $\alpha_c$ of the conversion of X-ray power absorbed in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ to the emitted light power is equal

$$\alpha_c = \beta \eta, \quad (1)$$

where $\beta$ is the efficiency of the generation of recombined electron–hole (e–h) pairs and $\eta$ is the part of e–h pairs that recombined with the radiation.

The generation efficiency of the recombined e–h pairs is determined by the ratio of the emitted photon energy $E_{hv}$ and the X-ray threshold energy $E_{th}$, which is required for the generation of a single e–h pair:

$$\beta = \frac{E_{hv}}{E_{th}}. \quad (2)$$

In conventional scintillators and X-ray luminescence screens, $E_{th} = 20–200 \, \text{eV}$ and $\beta \approx 1–10\%$, when X-ray power is converted to visible light of energy $E_{hv} \approx 2 \, \text{eV}$. Due to low $\beta$, the conventional X-ray luminescence screen has low brightness [5]. In $\text{Al}_x\text{Ga}_{1-x}\text{As}$ semiconductor material, $E_{th} = 4 \, \text{eV}$, and emitted light energy is $E_{hv} \approx 1.6 \, \text{eV}$. In this case, the efficiency is $\beta \approx 40\%$. This is a better performance than of the conventional X-ray–light converters [4].
The efficiency of radiative recombination is equal to

$$\eta = \frac{1}{1 + \tau_r/\tau_{nr}},$$  

where $\tau_r$ and $\tau_{nr}$ are the radiative and nonradiative recombination lifetimes, respectively. The $Al_xGa_{1-x}$As layer was doped by $Zn$ acceptors up to the concentration $p_{Zn} > 10^{18}$ cm$^{-3}$. It allows us to reduce $\tau_r < 10^{-9}$ s at $\tau_{nr} = 10^{-9}$ s and to obtain the efficiency of $\eta \approx 0.5 – 0.8$ in our $Al_xGa_{1-x}$As detectors. The measurements of the quantum efficiency $\alpha_c = \beta\eta$ of conversion of the absorbed X-ray power to light beam inside the $Al_xGa_{1-x}$As layer show that $\alpha_c \approx 20\%$, and it is better than in conventional X-ray luminophors or scintillators. The high efficiency $\alpha_c$ allows us to obtain higher signal-to-noise ratio in $Al_xGa_{1-x}$As detectors compared with conventional ones.

The external efficiency of X-ray–light conversion of the $Al_xGa_{1-x}$As detector is equal to

$$K_{ef} = \frac{E_{hv}}{E_{X0}},$$  

where $E_{hv}$ is the energy of light emitted by the detector and $E_{X0}$ is the energy of X-ray incident on the detector surface. $K_{ef}$ is determined by $\alpha_X$, the part of the X-ray photon energy absorbed in the $Al_xGa_{1-x}$As layer, quantum efficiency $\alpha_c$ (see Eq. (1)), and the efficiency $\gamma$ of light output from the graded-gap $Al_xGa_{1-x}$As structure:

$$K_{ef} = a_Xa_c\gamma.$$  

(5)

For soft X-rays ($E_{X0} < 20$ keV) and the $Al_xGa_{1-x}$As layer of the thickness $\approx 100 \mu m$ one has $a_X \approx 1$.

The output coefficient $\gamma$ is equal to

$$\gamma = \frac{TF}{1 – (1 – T)\eta/2},$$  

where $T = 4n(1 + n)^{-2}$ is the transparency, $F = \sin^2(\theta/2)$ is the factor of total internal reflection, and $\theta = \arcsin n^{-1}$. For the light output from GaAs to air: $n = 3.54$, $T = 0.69$, $\theta = 16^\circ$, $F \approx 2\%$. The factor $F$ reduces the conversion efficiency $K_{ef}$ most strongly.

Figure 4 shows emitted light measured at energy $E_{hv}$ (in CCD camera arbitrary units) as a function of the X-ray exposure time $t_{exp}$. The X-ray intensity used was constant, $W_{X0} = 5.3 \cdot 10^{-5}$ W/cm$^2$, and the X-ray energy $E_{X0}$ absorbed in the $Al_xGa_{1-x}$As layer was proportional to the exposure time: $E_{X0} = 5.3 \cdot 10^{-5} t_{exp}$ W·s·cm$^{-2}$.

The experimental results show that the external efficiency of X-ray–light conversion is low ($K \approx 10^{-2}$).
of different objects obtained by the CCD camera was used for determination of the contrast and spatial image resolution. It is shown that 1.5% luminescence signal variations can be discriminated on the PC monitor. The measurements of the spatial resolution of the Al$_x$Ga$_{1-x}$As detector were performed using a different type of the masks. It was found that the spatial resolution exceeded 20 lines/mm [3].

The high spatial resolution and contrast allows the Al$_x$Ga$_{1-x}$As detectors to be used for the X-ray detection of small objects.

3. Detectors with electric response

In spite of a much higher internal quantum efficiency of the X-ray conversion to light the graded-gap Al$_x$Ga$_{1-x}$As structures, as compared with scintillators, have low external light output efficiency, about a few percent. Consequently, X-ray imaging with the light-emitting Al$_x$Ga$_{1-x}$As detector needs a long exposure time which can reach up to a few seconds using a charge coupled device (CCD) camera [2].

Two processes are responsible for this low external quantum efficiency of the light-emitting Al$_x$Ga$_{1-x}$As detector. The first and the main is the strong internal reflection of light excited in the crystal at the Al$_x$Ga$_{1-x}$As/air interface (up to 98%), and the second is the extraction of e–h pairs generated by X-rays from the bulk of the Al$_x$Ga$_{1-x}$As layer by the internal, graded-gap electric field before their radiative recombination. The second process is important in thin graded-gap structures.

With the aim to eliminate these drawbacks of the light-emitting structures and to increase the X-ray detector sensitivity radically, new nonuniformly doped graded-gap Al$_x$Ga$_{1-x}$As structures with electric response were proposed and investigated [6].

Two types of graded-gap Al$_x$Ga$_{1-x}$As structures were investigated:

1. n-GaAs/p-Al$_x$Ga$_{1-x}$As structures with a p–n junction at the wide energy gap side ($x = 0.4$) of the graded-gap layer;
2. p-Al$_x$Ga$_{1-x}$As/n-GaAs structures with a p–n junction at the narrow energy gap side ($x = 0$) of the graded-gap layer.

A graded-gap layer was formed by changing the Al fraction $x$ across the layer thickness $L$ during the epitaxial growth process. The Al fraction varied from $x = 0.4$ at the substrate to $x = 0$ on the surface of the epitaxial graded-gap Al$_x$Ga$_{1-x}$As layer.

The first type of structures consisted of graded-gap Al$_x$Ga$_{1-x}$As layers ($L = 50 \mu$m) grown on an n-GaAs substrate. The graded-gap Al$_x$Ga$_{1-x}$As layer was doped by Zn up to a hole concentration $p \approx 10^{18}$ cm$^{-3}$.

The second type of structures was obtained by growing a Zn-doped graded-gap Al$_x$Ga$_{1-x}$As layer ($L = 15–30 \mu$m) and an additional thin (1–3 $\mu$m) n-GaAs layer on a p-GaAs substrate.

Figure 6 shows schematically the band diagrams of the grown structures. The operating mechanisms of these two types of structure are different depending on the graded-gap Al$_x$Ga$_{1-x}$As layer thickness. In the structures with a p–n junction at the wide gap side (Fig. 6(a)), X-rays excite luminescence in the graded-gap Al$_x$Ga$_{1-x}$As layer. This luminescence is transmitted through the wide-gap optical window to the GaAs p–n junction. The p–n junction photovoltaic or current response to the X-ray luminescence was measured. In thin p-Al$_x$Ga$_{1-x}$As/n-GaAs structures with the p–n junction in the narrow gap side (Fig. 6(a)), e–h pairs...
generated by X-rays in the graded-gap layer are extracted from the Al$_x$Ga$_{1-x}$As layer and collected at the $p-n$ junction by internal graded-gap field before recombination [6, 7]. The influence of internal graded-gap field to charge collection is observed in the experiment shown in Fig. 7. Two structures of different thickness with a potential barrier at the narrow gap side were removed from substrates and X-ray luminescence intensity and voltage response were measured. Photovoltaic response of the thin structure is higher than of the thick one, because of efficient charge collection. However, the luminescence intensity of the thin structure is much lower, because of fast charge extraction from the graded-gap layer. A tube with a Cr anode as a soft X-ray source (see Fig. 6(a)), where they are detected. The detection efficiency in the thick layer is defined mainly by the efficiency of light emission by generated carriers (Eq. (3)).

The voltage response at the junction is equal to

$$U_p = \frac{k_B T}{e} \ln \left(1 + \frac{j_{ph}}{j_s}\right),$$

where at room temperature $k_B T/e \approx 25$ meV.

Due to the large $E_g \approx 0.4$ eV, the heterojunction saturation current $j_s$ (see Fig. 6(a)) is determined mainly by hole current over the barrier $\varphi_p$:

$$j_s \sim p_0 \exp \left(\frac{\varphi_p}{k_B T}\right).$$

Because of large $E_g$ in the Al$_x$Ga$_{1-x}$As structure, $\varphi_p/(k_B T) \gg 1$, and $j_s \ll j_{ph}$ can be expected. Then,

$$U_p = \frac{k_B T}{e} \ln \frac{j_{ph}}{j_s}.$$

The voltage–absorbed power sensitivity is

$$\beta_v = \beta_j R_p [V/W],$$

where

$$R_p = \frac{U_p}{j_{ph}}.$$
The resistivity $R_p$ of the junction increases with decrease of $J_{ph} \sim W_{X \text{ abs}}$. Consequently, the volt–watt sensitivity

$$\beta_v \sim \frac{\ln W_{X \text{ abs}}}{W_{X \text{ abs}}} \quad (17)$$

increases when $W_{X \text{ abs}}$ decreases.

Figure 8 illustrates the measured dependences of $I_{ph}$ and $U_p$ on the X-ray power $W$ at the surface of the Al$_x$Ga$_{1-x}$As/GaAs detector. One can see that the dependence of the current $I_{ph}$ on the X-ray power $W_{X \text{ abs}}$ is linear and the dependence of $U_p$ is logarithmic, as predicted by Eqs. (8) and (14). The power absorbed in the detector is

$$W_{X \text{ abs}} = WS a_x, \quad (18)$$

where $S$ is the detector surface area and $a_x$ is the fraction of the X-rays absorbed in the Al$_x$Ga$_{1-x}$As layer. For a thick detector with a $p$–$n$ junction, $a_x(50 \mu m) \approx 0.78$ and $S_{pn} = 0.35 \text{ cm}^2$. For a thin detector with a $p$–$n$ junction $a_x(15 \mu m) \approx 0.45$ and $S_{pn} = 0.10 \text{ cm}^2$. The $a_x$ was estimated from the absorption of X-ray beam with the energy $E_X \approx 8 \text{ keV}$. In this estimate, the experimental data (Fig. 8) for the ampere–watt sensitivities, $\beta_j = 0.078 \text{ A/W}$ for the thick (50 $\mu$m) detector and $\beta_j = 0.226 \text{ A/W}$ for the thin (15 $\mu$m) detector, were used. The value of $\beta_j (15 \mu m)$ in the thin layer is close to the value 0.25 A/W, predicted by Eq. (11), and corresponds to 100% collection of charge generated in the detector bulk.

The ampere–watt sensitivity of the thin (15 $\mu$m) Al$_x$Ga$_{1-x}$As layer is higher than in the thick (50 $\mu$m) one, due to higher charge collection efficiency. But the 15 $\mu$m thick Al$_x$Ga$_{1-x}$As layer is transparent to X-ray photons with energies $E_X \geq 10 \text{ keV}$.

The observed volt–watt sensitivity, as follows from Eq. (17), is the largest at low absorbed power. At $W_{X \text{ abs}} \approx 10^{-7} \text{ W}$ the measured $\beta_v \approx 5 \times 10^5 \text{ V/W}$, and at $W_{X \text{ abs}} \approx 2 \times 10^{-6} \text{ W}$ it is $\beta_v \approx 1.1 \times 10^5 \text{ V/W}$.

This high volt–watt sensitivity, therefore, allows the use of Al$_x$Ga$_{1-x}$As/GaAs detectors in an X-ray diffractometer instead of the more complex scintillator–photomultiplier arrangement with its associated electronics. Figure 9 demonstrates the diffractogram of a graphite crystal using the X-ray beam from the X-ray source with a Cu anode. One can see that the characteristic line with energy $E_X = 8.04 \text{ keV}$ is very well resolved in this case. Note that the detector noise level is less than $10^{-1} \text{ mV}$.

The fact that the generated carriers are collected without application of any external bias voltage to the detector ensures a low level of noise. Only thermal noise remains as a noise source. This is an important advantage of the Al$_x$Ga$_{1-x}$As/GaAs X-ray and particle detectors compared with $p$–$n$ Si and Schottky barrier diodes which do need a bias voltage and have an additional noise contribution due to leakage current.

### 4. Detection of single $\alpha$-particles

A charge generated by a single particle with the energy $E_p$ in an Al$_x$Ga$_{1-x}$As layer of thickness $L$ is

$$Q_x(L) = q \frac{E_p [1 - \exp(-\alpha_p L)]}{E_{th}}, \quad (19)$$

where $q$ is the elementary charge, $E_p$ is the energy of the $\alpha$-particle, $\alpha_p$ is the linear attenuation coefficient of the $\alpha$-particle in the Al$_x$Ga$_{1-x}$As layer, and $E_{th}$ is the threshold energy for charge collection.
penetration depth into GaAs is 23 µm. So, graded-gap Al$_x$Ga$_{1-x}$As structures of 27 µm thickness were used for alpha particles detection. A 100% generated charge collection without application of any external bias voltage was attained. The measured energy spectra of $^{241}$Am alpha particles using the graded-gap Al$_x$Ga$_{1-x}$As structure are shown in Fig. 10. Since the bias voltage is absent, the noise level is much lower than the amplitude of the collected charge signal [8].

5. Multiplication of collected charge in the $n^-$-GaAs layer

The $n^-$-GaAs/$p^+\text{-}Al_xGa_{1-x}$As structure was prepared for observing the charge multiplication effect. A thin ($l_n < 10^{-4}$ cm) low-doped ($n = 10^{15}$ cm$^{-3}$) $n^-$-GaAs layer was grown at the narrow-gap side of high-doped ($p = 10^{18}$ cm$^{-3}$) $p^+\text{-}Al_xGa_{1-x}$As layer ($L = 20$ µm).

In order to multiply the collected charge, the drift time through the thin $n^-$-GaAs layer $t_{dr}(t_n)$ has to be less than the carrier recombination time $\tau$ in this layer. The recombination time, experimentally found from the relaxation of photoconductivity in the low-doped $n^-$-GaAs layer, was $\tau \approx 5 \times 10^{-6}$ s. It appeared to be much larger than in the high-doped Al$_x$Ga$_{1-x}$As layer.

To satisfy the condition $t_{dr} < \tau$ the reverse voltage is applied to the $n^-$-GaAs/$p^+\text{-}Al_xGa_{1-x}$As heterojunction. At the breakdown of the $p - n$ junction, the increased reverse current $I_0$ also increases the electric field in $n^-$-GaAs, and as a result, the drift time $t_{dr}$ decreases.

Figure 11 shows the schematic band diagram of the $n^-$-GaAs/$p^+\text{-}Al_xGa_{1-x}$As structure at application of reverse voltage to the structure. Because of the proportionality, $t_{dr} \sim v_{dr}^{-1} \sim I_0^{-1}$, the current multiplication coefficient $K = \tau/t_{dr}$ is proportional to the bias current $I_0$.

The charge collected from the $n^-$-GaAs layer is equal to the charge collected from the Al$_x$Ga$_{1-x}$As layer $Q_c$, multiplied by a factor $K$:

$$Q_I = Q_c K.$$  \hspace{1cm} (25)

The short-circuit current through the structure is

$$I_D = I_0 + I_X K, \quad I_X = \beta P_{abs},$$  \hspace{1cm} (26)

where $P_{abs}$ is the absorbed X-ray power and $\beta$ is the current/absorbed power sensitivity. For the structure Al$_x$Ga$_{1-x}$As/GaAs one finds that $\beta = 0.25\eta$ (see Eq. (11)).
sorbed X-ray power at different bias currents and the electron flow in the graded-gap field. $I_0$ indicates the $p-n$ junction reverse current.

Figure 11. The schematic band diagram of the $n^-$-GaAs/p$^+$-Al$_x$Ga$_{1-x}$As heterostructures with applied reverse voltage. $I_X$ denotes the electron flow in the graded-gap field. $I_0$ indicates the $p-n$ junction reverse current.

The multiplication of the collected charge increases with increasing $I_0$ and achieves $K = 234$ at $I_0 = 0.97 \mu A$. Correspondingly, the current/absorbed power sensitivity increases by a factor of 234 and achieves $\beta = 17.5 \text{ A/W}$. This is 70 times larger than the sensitivity $\beta = 0.25 \text{ A/W}$ in the case of 100% collection of charge generated in Al$_x$Ga$_{1-x}$As. Note that the amplification effect is obtained at applied reverse bias of only a few volts (Fig. 12). Due to the multiplication effect, the novel X-ray radiation detectors are much more sensitive than conventional $p-n$ Si or GaAs detectors.

6. Conclusions

1. Al$_x$Ga$_{1-x}$As layers of the thickness up to 100 $\mu$m absorb efficiently X-ray power in the range of $E_X = 3-10$ keV, and they can be used as soft X-ray–light converters. Detectors of area $2 \times 3 \text{ cm}^2$ with homogeneous luminescence were fabricated. It is shown experimentally by the direct read-out of the Al$_x$Ga$_{1-x}$As layer X-ray luminescence image by the CCD camera that the contrast and spatial resolution of the image details is better than 15 lines/mm.

2. The volt–watt efficiency $\beta_v$ increases with decreasing X-ray power. Values of $\beta_v = 1.1 \times 10^5 \text{ V/W}$ at $W_{X abs} = 2 \times 10^{-6}$ W and $\beta_v = 5 \times 10^5 \text{ V/W}$ at $W_{X abs} \approx 2 \times 10^{-7}$ W are observed with the thin 15 $\mu m$ Al$_x$Ga$_{1-x}$As layers. A 100% charge collection efficiency is achieved in a 27 $\mu m$ thick Al$_x$Ga$_{1-x}$As detector without application of any external bias voltage.

3. The charge generated by the ionizing radiation in the $p^+$-Al$_x$Ga$_{1-x}$As layer is collected by graded-gap field and directed to thin $n^-$-GaAs where it is multiplied. The new charge multiplication method by increasing the $n^-p^+$-heterojunction reverse current is realized. The achieved collected charge multiplication in $n$-GaAs/p$^+$-graded-gap Al$_x$Ga$_{1-x}$As structures exceeds 200. The current response $\beta$ of the new detector is much larger than in conventional Si or GaAs detectors.

4. The new structure can be used as a high efficiency single particle detector ($^{241}$Am alpha particles) operating without application of any bias.

References


VARIZONINIO Al_{x}Ga_{1−x}As JONIZUOJANČIOS SPINDULIUOTĖS JUTIKLIAI

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Santrauka

Pateikti varizoninių Al_{x}Ga_{1−x}As jonizuojančios spinduliuotės jutiklių tyrimai bei jutiklių su optiniu ir elektriniu atsakais veikimo mechanizmai. 2 × 3 cm² ploto jutikliuose pasiektas didelis vidinis Röntgen'o spinduliuotės pavertimo šviesos efektyvumas ir vaizdo erdvine skyla, geresnė negu 15 linijų/mm. Pagrindinė išorinė efektyvumą mažinant priežastis yra mažas visiškio atspindžio kampas nuo jutiklio paviršiaus. Pasiektas 100% jonizuojančios spinduliuotės generuoto krūvio surinkimas 27 µm storio Al_{x}Ga_{1−x}As sluoksnyje vidiniu varizoniniu lauku, neprijungus jokios išorinės žtampos. Parodyta, kad varizoniniai p-Al_{x}Ga_{1−x}As/n-GaAs dariniai be išorinio postūmio gali būti naudojami pavieniems jonizuojančioms dalelėms (^{241}Am alfa dalelės) detektuoti. Realizuotas naujas surinkto krūvio dauginimo metodas p⁺-Al_{x}Ga_{1−x}As/n-GaAs dariniuose didinant atgalinę p⁺−n− sandėros srovę. Pasiektas stipriūnų koefficento vertė viršija du šimtus, o jutiklio srovės jautris padidėja iki 17,5 A/W ir gerokai viršija prastinių pušlaidininkinių Si ir GaAs jutiklių jautrį.