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(54) **HIGH SPEED PIN PHOTODIODE WITH INCREASED RESPONSIVITY**

SCHNELLE PHOTODIODE MIT ERHÖHTER EMPFINDLICHKEIT

PHOTODIODE PIN À GRANDE VITESSE AVEC UNE SENSIBILITÉ AMÉLIORÉE

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- **NICCOL GBP O RINALDI: "Analysis of the Depletion Layer of Exponentially Graded P-N Junctions with Nonuniformly Doped Substrates", IEEE TRANSACTIONS ON ELECTRON DEVICES, IEEE SERVICE CENTER, PISACATAWAY, NJ, US, vol. 47, no. 12, 1 December 2000 (2000-12-01), XP011017449, ISSN: 0018-9383**
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- **JORDAN A G ET AL: "Photoeffect on diffused P-N junctions with integral field gradients", IRE TRANSACTIONS ON ELECTRON DEVICES, IEEE, USA, vol. 2, no. 4, 1 October 1960 (1960-10-01), pages 242-251, XP011221859, ISSN: 0096-2430**

Description

FIELD OF THE INVENTION

[0001] The present invention relates to a semiconductor-based photodetector, and in particular to a high-speed, broad bandwidth photodetector having enhanced absorption characteristics.

BACKGROUND AND SUMMARY OF THE INVENTION

[0002] There is a well-known tradeoff between high speed and sensitivity in a photodetector. High bandwidth signal detection requires a short transit time of the carriers and thus a thin absorption layer. However, the geometrical constraints on the absorption layer thickness results in a reduced absorption and lower responsivity.

[0003] One type of semiconductor-based photodetector is termed a p-i-n junction diode, or a PIN diode. This type of structure is generally composed of a number of solid semiconductive sandwiched together in an epitaxial structure. In particular, a p-type semiconductor material and an n-type semiconductor region are separated by an intrinsic semiconductor.

[0004] In a PIN diode, the depletion layer extends into each side of junction by a distance that is inversely proportional to the doping concentration. Thus, the p-i depletion layer extends well into the intrinsic material, as does the depletion layer of the i-n junction. Accordingly, a PIN diode functions like a p-n junction with a depletion layer that encompasses the entirety of the intrinsic material. The primary advantages inherent to this structure are twofold. First, the addition of the intrinsic layer permits a fractional increase in the amount of light to be captured by the diode. Secondly, due to the extended depletion layer, the PIN diode has a very small junction capacitance and corresponding fast response.

[0005] Most attempts at increasing the speed of PIN diodes have focused on reducing the capacitance at the junction. At least one proposed design has included an undoped drift region for this purpose, effectively increasing the size of the intrinsic portion of the diode. Although this solution is suitable for decreasing the junction capacitance, it unfortunately increases the transit time for the carriers and thus reduces the response time of the photodetector. As such, there is a need in the art for an improved photodetector that strikes the proper balance between capacitance and response time, while increasing the responsivity of the device.

[0006] The document Jordan et al, "Photoeffect on Diffused P-N Junctions with Integral Field Gradients", IRE transactions on electron devices, vol. 2, no. 4, p. 242-251 discloses a PN photodiode having an exponentially graded p-type dopant concentration. The thereby provided built-in field lowers the electron component of the dark current and reduces the transient time of the electrons considerably. This leads to an improved frequency response of the photodiode.

[0007] Accordingly, the present invention refers to a PIN photodiode in accordance with the subject-matter of claim 1. The photodiode has a first p-type semiconductor layer and an n-type semiconductor layer coupled by a second p-type semiconductor layer. The second p-type semiconductor layer has graded doping along the path of the carriers. In particular, the doping is concentration graded from a high value near the anode to a lower p concentration towards the cathode. By grading the doping in this way, an increase in absorption is achieved, improving the responsivity of the device. Although this doping increases the capacitance relative to an intrinsic semiconductor of the same thickness, the pseudo electric field that is created by the graded doping gives the electrons a very high velocity which more than compensates for this increased capacitance. Further embodiments and advantages of the present invention are discussed below with reference to the figures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008]

Figure 1 is an energy band diagram of a pin photodiode in accordance with the present invention.

Figure 2 is a cross-sectional view of a basic configuration of a pin photodiode in a surface illuminated structure in accordance with the present invention.

Figure 3 is a graph representing the relationship between the electric field and the electron velocity according to an aspect of the present invention.

Figure 4 is a graph representing the relationship between the doping concentration and the relative depth of a semiconductor layer of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0009] In accordance with the present invention, an epitaxial structure is provided for photoconductive purposes. The photoconductive structure is a modified PIN diode that is optimized for increased performance through an enhanced layer having a graded doping concentration. The particulars of the structure and method of manufacture of the present invention are discussed further herein.

[0010] Referring to Figure 1, an energy band diagram of a PIN photodiode 10 shows the relative energy levels of the semiconductor materials that form the photodiode 10. In particular, the photodiode 10 is comprised of a group of semiconductor materials, including a first p-type semiconductor layer 14, a second p-type semiconductor layer 16, and an n-type semiconductor layer 18. An anode layer 12 is shown adjacent to the first p-type semiconductor layer 14 to collect holes.

[0011] The first p-type semiconductor layer 14 is selected from a group comprising tertiary semiconductors, or group III-V semiconductors. Accordingly, the first p-type semiconductor layer 14 is either two elements from group III combined with one element from group V or the converse, two elements from group V combined with one element from group III. A table of representative groups of the periodic table is shown below.

GROUP II	GROUP III	GROUP IV	GROUP V
Zinc (Zn)	Aluminum (Al)	Silicon (Si)	Phosphorus (P)
Cadmium (Cd)	Gallium (Ga)	Germanium (Ge)	Arsenic (As)
Mercury (Hg)	Indium (In)		Antimony (Sb)

[0012] In the preferred embodiment, the first p-type semiconductor layer 14 is InAlAs. However, it is understood that the first p-type semiconductor layer 14 may be any tertiary semiconductor that provides the necessary bandgap for optimized operation of the photodiode 10.

[0013] The n-type semiconductor layer 18 is also selected from a group comprising tertiary semiconductors, or group III-V semiconductors. As before, the n-type semiconductor layer 18 is either two elements from group III combined with one element from group V or the converse, two elements from group V combined with one element from group III. In the preferred embodiment, the n-type semiconductor layer 18 is InAlAs. However, it is understood that the n-type semiconductor layer 18 may be any tertiary semiconductor that provides the necessary bandgap for optimized operation of the photodiode 10.

[0014] The second p-type semiconductor layer 16 is also selected from a group comprising tertiary semiconductors, or group III-V semiconductors. In the preferred embodiment, the second p-type semiconductor layer 16 is InGaAs with a graded doping concentration. However, it is understood that the second p-type semiconductor layer 16 may be any tertiary semiconductor that provides the necessary low bandgap for optimized operation of the photodiode 10.

[0015] In order to achieve a graded doping concentration, the second p-type semiconductor layer 16 is not doped in a typical manner. In general, a p-type semiconductor is fabricated by using dopants with a deficiency of valence electrons, also known as acceptors. The p-type doping results in an abundance of holes. For example, in a type III-V semiconductor, some of the group III atoms may be replaced with atoms from group II, such as Zn or Cd, thereby producing a p-type material. Similarly, as group IV atoms act as acceptors for group V atoms and donors for group III atoms, a group IV doped III-V semiconductor will have an excess of both electrons and holes.

[0016] Figure 2 is a cross-sectional view of a basic configuration of a photodiode 10 in a surface illuminated structure designed in accordance with the present invention. A substrate layer 20 is provided for growing the semiconductor structure. The n-type semiconductor layer 18 is deposited upon the substrate. The first p-type semiconductor layer 14 and the second p-type semiconductor layer 16 are deposited in a manner such that the second p-type semiconductor layer 16 is directly adjacent to the n-type semiconductor layer 18. As before, an anode layer 12 is deposited on the first p-type semiconductor layer 14 for collecting holes. Also shown is a cathode layer 22, or n-type contact layer, for collecting electrons.

[0017] As noted, it is a feature of the second p-type semiconductor layer 16 that it includes a graded doping concentration. The presence of dopants in the second p-type semiconductor layer 16 is controlled in order to optimize the performance of the photodiode. A first concentration 15 is located near the first p-type semiconductor 14, and a second concentration 17 is directly adjacent to the n-type semiconductor 18. Preferably, a depth D of the second p-type semiconductor layer 16 is between 800 and 1,000 angstroms deep, i.e. the dimension parallel to the travel of the carriers.

[0018] In the preferred embodiment, the first concentration 15 is greater than the second concentration 17. In particular, the first concentration 15 is located at a position x_o and defines a dopant concentration p_o. A preferred doping concentration gradient is governed by the following equation:

$$(1) \qquad p = p_o e^{\frac{-x}{D}}$$

over the depth D of the second p-type semiconductor layer 16 for all x and D greater than zero. A generic representation of the dopant concentration p is shown in Figure 4.

[0019] The graded doping structure of the second p-type semiconductor layer 16 results in improved performance of the photodiode 10. During operation, incident light is absorbed in the second p-type semiconductor layer 16 of the photodiode 10. The light that is absorbed in the second concentration 17 part of the second p-type semiconductor layer 16 produces electrons and holes which drift to the anode 12 and cathode 22 under the influence of the large drift electric field. Although this is the usual situation in standard uniformly low doped absorber PIN photodetectors, in the present invention, the photoresponse of the carriers is more complex.

[0020] The electrons generated in the second concentration 17 part of the second p-type semiconductor layer 16 reach the cathode with their saturation velocity and are collected. The holes generated in the second concentration 17 part of the second p-type semiconductor layer 16 travel to the anode 12, thus entering the first concentration 15 where the concentration of dopants is relatively high and where they are collected, thus ending their transit time.

[0021] By way of comparison, the light that is absorbed in the first concentration 15 part of the second p-type semiconductor layer 16 also produces electrons and holes. In this case however, the holes are readily collected in the first concentration 15 and thus do not add substantially to the transit time of the carriers or reduce the bandwidth of the photodiode 10. Accordingly, insofar as the holes are concerned, the graded doping concentration of the photodiode 10 does not add to their transit time or reduce the detector bandwidth in either in the first concentration 15 or the second concentration 17.

[0022] Another aspect of the graded doping concentration of the second p-type semiconductor layer 16 is the creation of a pseudo-electric field. The electrons generated in the first concentration 15 region are subject to this pseudo-field shown below as

$$E = -\left(\frac{kT}{q}\right)\frac{dp}{dx}\,\frac{1}{p}, \tag{2}$$

where k is Boltzman's constant, T is the temperature, q is the charge of an electron, and the value $\frac{dp}{dx}$ is the doping concentration gradient.

[0023] The pseudo-field E produces an "overshoot" electron velocity, i.e. the electron velocity is potentially many times faster than the saturation velocity. A typical electron saturation velocity is on the order of $5x10^6$ cm/sec. However, the exponential gradient shown in Equation (1) with D=1,000 angstroms yields a field E=2.5kV/cm, which corresponds to an electron overshoot velocity as large as $3x10^7$ cm/sec. A graph depicting the relationship between the magnitude of the pseudo-field E and the electron velocity is shown in Figure 3.

[0024] As described, the present invention improves upon the state of the art in photodiodes by implementing a graded doping concentration in the intrinsic region of a PIN photodiode. In such a manner, the net absorption of a photodiode can be increased without substantially reducing the overall bandwidth of the device. It is further understood that it may be advantageous to optimize the overall speed by adjusting the doping concentration, the capacitance of the device, and the total thickness of the absorption region. It should be apparent to those skilled in the art that the above-described embodiments are merely illustrative of but a few of the many possible specific embodiments of the present invention.

Claims

1. A PIN photodiode (10) comprising:

a first p-type semiconductor layer (14);
an n-type semiconductor layer (18);
a second p-type semiconductor layer (16) disposed between the first p-type semiconductor layer (14) and the n-type semiconductor layer (18) such that the second p-type semiconductor (16) is directly adjacent to the n-type semiconductor (18), the second p-type semiconductor layer (16) having a graded doping concentration;
a substrate (20), the n-type semiconductor layer (18) being grown on the substrate (20);
an anode layer (12) for collecting holes;
a cathode layer (22) for collecting electrons;
wherein the graded doping concentration defines a first concentration (15) adjacent to the first p-type semiconductor layer (14) and a second concentration (17) adjacent to the n-type semiconductor layer (18), and further

wherein the first concentration (15) is greater than the second concentration (17);
wherein incident light is absorbed in the second p-type semiconductor layer (16), the incident light that is absorbed in the second concentration (17) part of the second p-type semiconductor layer (16) produces electrons and holes which drift to the anode and cathode;
wherein electrons generated in the second concentration (17) part of the second p-type semiconductor layer (16) reach the cathode with their saturation velocity and are collected, the holes generated in the second concentration (17) part of the second p-type semiconductor layer (16) travel to the anode (12),
wherein the incident light that is absorbed in the first concentration (15) part of the second p-type semiconductor layer (16) produces electrons and holes, wherein the holes are collected in the first concentration (15) part;
and wherein said electrons in the first concentration (15) part are subject to a pseudo field capable of providing them with an overshoot electron velocity, the pseudo field being governed by the following equation:

$$E = -\left(\frac{kT}{q}\right)\frac{dp}{dx}\;\frac{1}{p},$$

where k is Boltzman's constant, T is the temperature, q is the charge of an electron, and the value $\frac{dp}{dx}$ is the doping concentration gradient, and
wherein the first concentration (15) is located at a position x_o and defines a concentration p_o, and further wherein the graded doping concentration is governed by the following equation:

$$p = p_o e^{\frac{-x}{D}}$$

over the depth D of the second p-type semiconductor layer (16) for all x and for D greater than zero.

2. The photodiode of claim 1 wherein the first p-type semiconductor layer (14) is InAlAs.

3. The photodiode of claim 1 wherein the n-type semiconductor layer (18) is InAlAs.

4. The photodiode of claim 1 wherein the second p-type semiconductor layer (16) is InGaAs.

5. The photodiode of one of the foregoing claims wherein the depth D is between 800 and 1000 angstroms in length.

Patentansprüche

1. PIN-Photodiode (10), die folgendes aufweist:

eine erste p-Typ-Halbleiterschicht (14);
eine n-Typ-Halbleiterschicht (18);
eine zweite p-Typ-Halbleiterschicht (16), die zwischen der ersten p-Typ-Halbleiterschicht (14) und der n-Typ-Halbleiterschicht (18) so angeordnet ist, dass die zweite p-Typ-Halbleiterschicht (16) direkt an die n-Typ-Halbleiterschicht (18) anschließt, wobei die zweite p-Typ-Halbleiterschicht (16) eine abgestufte Dotierungskonzentration aufweist;
ein Substrat (20), wobei die n-Typ-Halbleiterschicht (18) auf dem Substrat (20) gezüchtet wurde;
eine Anodenschicht (12) zum Sammeln von Löchern;
eine Kathodenschicht (22) zum Sammeln von Elektronen;

wobei die abgestufte Dotierungskonzentration eine erste Konzentration (15) anschließend an die erste p-Typ-Halbleiterschicht (14) und eine zweite Konzentration (17) anschließend an die n-Typ-Halbleiterschicht (18) definiert, und weiterhin wobei die erste Konzentration (15) größer ist als die zweite Konzentration (17);
wobei einfallendes Licht in der zweiten p-Typ-Halbleiterschicht (16) absorbiert wird, das einfallende Licht, das in dem zweiten Konzentrations (17)-Abschnitt der zweiten p-Typ-Halbleiterschicht (16) absorbiert wird, Elektronen und Löcher erzeugt, die zur Anode und Kathode wandern;

wobei im zweiten Konzentrations (17)-Abschnitt der zweiten p-Typ-Halbleiterschicht (16) erzeugte Elektronen die Kathode mit ihrer Sättigungsgeschwindigkeit erreichen und gesammelt werden, die in der zweiten Konzentrations (17)-Abschnitt der zweiten p-Typ-Halbleiterschicht (16), erzeugten Löcher zur Anode (12) wandern;
wobei das einfallende Licht, das im ersten Konzentrations (15)-Abschnitt der zweiten p-Typ-Halbleiterschicht (16) absorbiert wird, Elektronen und Löcher erzeugt, wobei die Löcher im ersten Konzentrations (15)-Abschnitt gesammelt werden;
wobei die Elektronen im ersten Konzentrations (15)-Abschnitt einem Pseudo-Feld unterzogen werden, das in der Lage ist, ihnen eine Elektronen-Überhöhungsgeschwindigkeit zu verleihen, wobei das Pseudofeld durch die folgende Gleichung vorgegeben wird:

$$E = -\left(\frac{kT}{q}\right)\frac{dp}{dx}\ \frac{1}{p},$$

wobei k die Boltzmann-Konstante ist, T die Temperatur ist, q die Ladung eines Elektrons ist, und der Wert *dp*/*dx* der Dotierungskonzentrationsgradient ist, und
wobei die erste Konzentration (15) an einer Position x_0 liegt und eine Konzentration p_0 definiert, und weiterhin wobei die abgestufte Dotierungskonzentration durch die folgende Gleichung:

$$p = p_o e^{\frac{-x}{D}}$$

über die Tiefe D der zweiten p-Typ-Halbleiterschicht (16) für alle x und für D größer als Null vorgegeben wird.

2. Photodiode nach Anspruch 1, wobei die erste p-Typ Halbleiterschicht (14) InAlAs ist.

3. Photodiode nach Anspruch 1, wobei die n-Typ Halbleiterschicht (18) InAlAs ist.

4. Photodiode nach Anspruch 1, wobei die zweite p-Typ Halbleiterschicht (16) InGaAs ist.

5. Photodiode nach einem der vorangehenden Ansprüche, wobei die Tiefe D in der Länge zwischen 800 und 1000 Å beträgt.

Revendications

1. Photodiode PIN (10), comprenant :

une première couche de semi-conducteur de type p (14) ;
une couche de semi-conducteur de type n (18) ;
une seconde couche de semi-conducteur de type p (16) disposée entre la première couche de semi-conducteur de type p (14) et la couche de semi-conducteur de type n (18) de telle sorte que le second semi-conducteur de type p (16) est directement adjacente au semi-conducteur de type n (18), la seconde couche de semi-conducteur de type p (16) ayant une concentration de dopage graduée ;
un substrat (20), la couche de semi-conducteur de type n (18) étant développée sur le substrat (20) ;
une couche d'anode (12) pour collecter des trous;
une couche de cathode (22) pour collecter des électrons ;

dans laquelle la concentration de dopage graduée définit une première concentration (15) adjacente à la première couche de semi-conducteur de type p (14) et une seconde concentration (17) adjacente à la couche de semi-conducteur de type n (18), et en outre dans laquelle la première concentration (15) est supérieure à la seconde concentration (17) ;
dans laquelle la lumière incidente est absorbée dans la seconde couche de semi-conducteur de type p (16), la lumière incidente qui est absorbé dans la partie de seconde concentration (17) de la seconde couche de semi-conducteur de type p (16) produit des électrons et des trous qui dérivent vers l'anode et la cathode ;
dans laquelle des électrons générés dans la partie de seconde concentration (17) de la seconde couche de semi-

conducteur de type p (16) atteignent la cathode à leur vitesse de saturation et sont collectés, les trous générés dans la partie de seconde concentration (17) de la seconde couche de semi-conducteur de type p (16) se déplacent jusqu'à l'anode (12),
dans laquelle la lumière incidente qui est absorbée dans la partie de première concentration (15) de la seconde couche de semi-conducteur de type p (16) produit des électrons et des trous, dans laquelle les trous sont collectés dans la partie de première concentration (15) ; et
dans laquelle lesdits électrons dans la partie de première concentration (15) sont soumis à un pseudo champ capable de leur fournir une vitesse d'électrons de dépassement, le pseudo champ étant régi par l'équation suivante :

$$E = -\left(\frac{kT}{q}\right)\frac{dp}{dx}\ \frac{1}{p},$$

où k est la constante de Boltzman, T est la température, q est la charge d'un électron, et la valeur $\frac{dp}{dx}$ est le gradient de concentration de dopage, et
dans laquelle la première concentration (15) est située à une position x_o et définit une concentration p_o, et dans lequel, en outre, la concentration de dopage graduée est régie par l'équation suivante :

$$p = p_o e^{\frac{-x}{D}}$$

sur la profondeur D de la seconde couche de semi-conducteur de type p (16) pour tout x et pour D supérieur à zéro.

2. Photodiode selon la revendication 1, dans laquelle la première couche de semi-conducteur de type p (14) est de type InAlAs.

3. Photodiode selon la revendication 1, dans laquelle la couche de semi-conducteur de type n (18) est de type InAlAs.

4. Photodiode selon la revendication 1, dans laquelle la seconde couche de semi-conducteur de type p (16) est de type InGaAs.

5. Photodiode selon l'une des revendications précédentes, dans laquelle la profondeur D est comprise entre 800 et 1000 angströms de longueur.

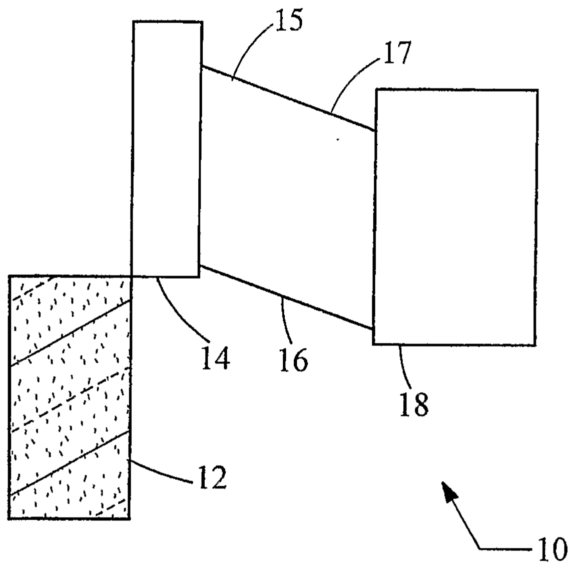


Fig. 1

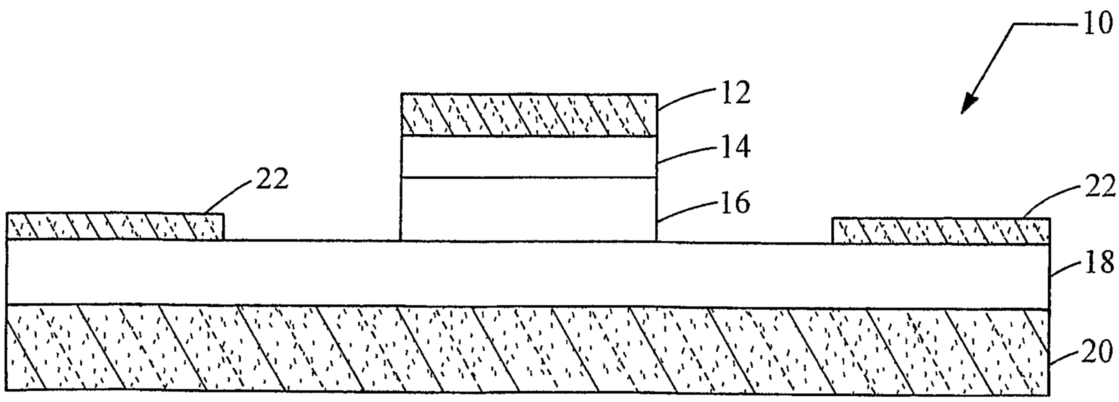
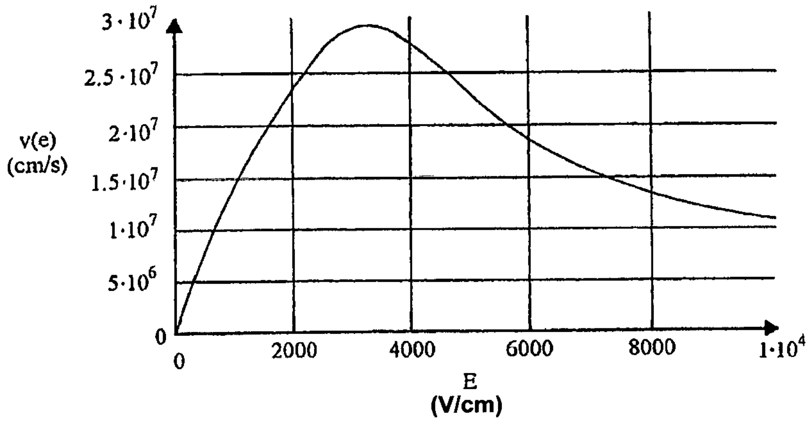


Fig. 2


3·10^7
2.5·10^7
v(e)
(cm/s)
2·10^7
1.5·10^7
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5·10^6
0
0
2000
4000
6000
8000
1·10^4
E
(V/cm)

Fig. 3

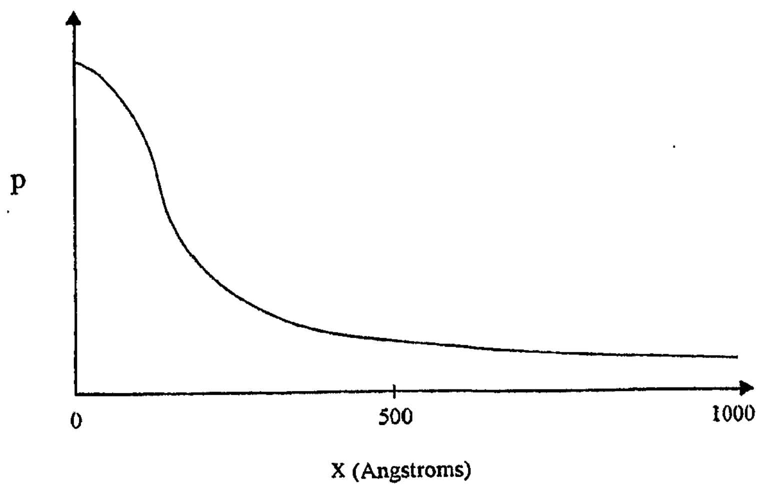
p
0
500
1000
X (Angstroms)

Fig. 4

REFERENCES CITED IN THE DESCRIPTION

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Non-patent literature cited in the description

- **JORDAN et al.** Photoeffect on Diffused P-N Junctions with Integral Field Gradients. *IRE transactions on electron devices,* vol. 2 (4), 242-251 **[0006]**