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A New Structure of an N-Channel Junction Field-Effect Transistor Embedded in a Pin Diode for an X-Ray Detector

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A new structure of an n-channel junction field-effect transistor (n-channel JFET) embedded in a pin diode for an X-ray detector is proposed. When a p/n junction, which is formed on the n^- substrate (i. e., i layer) of the pin diode around the JFET, is reverse-biased, the depletion region is extended under the n channel of the JFET, because the donor density of the n^- substrate is as low as 2×10^{12} cm^{-3}. This indicates that the n channel can be electrically separated from the n^- substrate, without a p region under the n channel. Since it is unnecessary to form the p region under the n channel, only one type of donor exists in the n channel of the JFET proposed here, suggesting that this n-channel JFET has the advantage of high performance due to high mobility and a low noise characteristic due to low defect densities.

KEYWORDS: JFET, n channel, X-ray detector, high mobility, low noise

1. Introduction

Semiconductor detectors have been developed for energy measurements, for example, for use in X-ray spectroscopy. Silicon drift detectors enable the realization of large-area X-ray detectors with spectroscopic energy resolution.[1,2] X-ray detectors that are required to measure a small number of electrons produced by X-ray irradiation are very sensitive to noise. Using a 1 keV X-ray, for example, only about 3×10^2 electrons are produced in silicon (Si). Long wiring between a pin diode for an X-ray detector (referred to as an X-ray pin diode) and the first transistor (i. e., a preamplifier) suffers from electromagnetic noise. Moreover, since a large stray capacitance resulting from the long wiring is added in parallel to the input capacitance of the preamplifier, the gain of the preamplifier is reduced at high frequencies. In order to shorten the wiring, therefore, it is necessary to embed the preamplifier in the substrate of the X-ray pin diode. Up to now, many preamplifiers embedded in X-ray pin diodes have been proposed and investigated.[3–6]

When a high-resistivity n-type Si (n^- Si) substrate is used for X-ray pin diodes, the drift of electrons with mobility much higher than that of holes can be taken advantage of. Moreover, the depletion region, where electrons produced by X-rays drift due to the electric field, can be easily extended over the whole i layer (n^- Si substrate) of the X-ray pin diode. In order to fabricate an n-channel junction field-effect transistor (n-channel JFET) as a preamplifier, a deep p region and a shallow n-channel region should be formed, as shown in Fig. 1(a).[3] The p region is required to electrically separate the n channel of the JFET from the i layer of the X-ray pin diode. In this case, the n-channel region includes both ionized acceptors and ionized donors. In order to avoid the generation of thermal noise in X-ray pin diodes and first JFETs, the operating temperature of these devices should be low. Since, at low temperatures, the mobility of electrons decreases with the total density of ionized donors and ionized acceptors, it is desirable to dope the channel of the JFET with one type of impurity. Moreover, defects formed due to doping with two types of impurities result in high 1/f noise.[4] Although the channel of the p-channel JFET (Fig. 1(b)) is doped with only one type of impurity, the mobility of holes is much lower than that of electrons, indicating that the performance of the p-channel JFET is poorer than that of the n-channel JFET.

In this letter, we propose a new structure of an n-channel JFET on the n^- substrate, without the p region under the n channel. Because the donor density of the n^- Si substrate is rather low, the depletion region, which is formed by the reverse-biased p/n junction on the n^- substrate around the JFET, can cover the n channel and can separate the n channel from the n^- substrate electrically. Since this n-channel JFET includes only one type of impurity in the channel, it could be expected that it has the advantage of high performance due to high mobility and a low noise characteristic due to low defect densities.

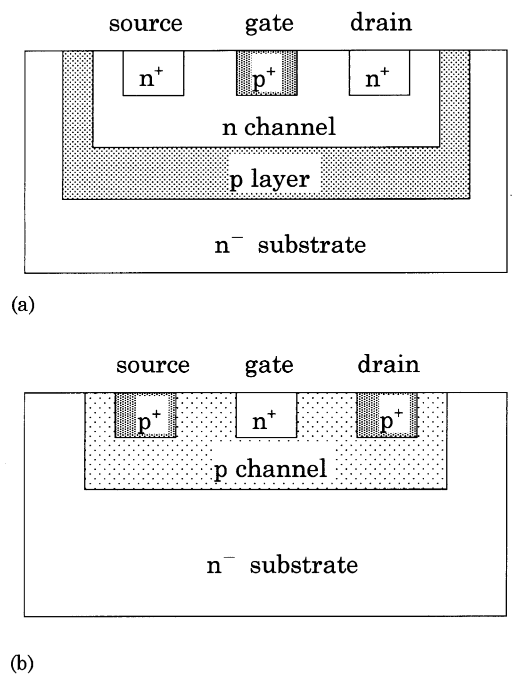

Fig. 1. Schematic cross sections of (a) n-channel JFET and (b) p-channel JFET in n^- substrate.

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2. A New N-Channel JFET Embedded in an X-ray Pin Diode

Since the resistivity of the n^- Si substrate for X-ray pin diodes is as high as 2×10^3 Ω·cm, the donor density in the n^- substrate is as low as 2×10^{12} cm^{-3}, indicating that a p/n junction can produce the wide depletion region in the n^- substrate. When the diffusion voltage of the p/n junction is 0.7 V, for example, the width of the depletion region in the n^- substrate is about 22 μm. When the n-channel JFET is introduced between two p/n junctions, as shown in Fig. 2, the n-channel JFET can be covered with this depletion region, suggesting that the n channel is electrically separated from the substrate, without the p region under the n channel shown in Fig. 1(a).

Since the width of the depletion region formed by the p/n junction increases with the reverse bias voltage applied to the p/n junction, the size of this n-channel JFET can be increased.

Let us consider an n-channel JFET with gate length $L =$ 4 μm, gate width $W = 50$ μm, gate depth $D = 1$ μm, and the distance between two p^+ rings $R = 36$ μm. The donor density (N_{chan}) of the n channel is 1×10^{17} cm^{-3} and the donor density (N_{sub}) of the n^- substrate is $2 \times 10^{12}\text{cm}^{-3}$. The diffusion voltages (V_{dr} and V_{dg}) formed by the p^+ ring and the p^+ gate are 0.69 V and 0.97 V, respectively.

Figure 3 shows the potential for electrons from the bottom of the gate toward the n^- substrate along the Z-Z' line in Fig. 2. The set of potentials for five reverse bias voltages ($-V_{\text{ring}}$) applied to the p^+ ring are shown in this figure. The diffusion voltage V_{dg} forms the approximately 0.15-μm-wide depletion region in the channel. At $-V_{\text{ring}} = 0$ V, even electrons with energy as low as 0.4 eV can be injected from the n channel into the n^- substrate. Moreover, electrons produced by X-rays can easily transfer from the n^- substrate to the n channel. However, at the other V_{ring} in Fig. 3, it is found that the depletion region formed by the p^+ ring separates the n channel from the n^- substrate completely. In other words, this separation prevents electrons produced by X-rays from being injected into the n-channel and it also keeps electrons flowing in the channel from diffusing toward the n^- substrate.

On the other hand, the effective depth (D_{eff}) of the channel is narrowed by the depletion region formed by the p^+ ring. Corresponding to $-V_{\text{ring}}$ of 0 V, -5 V, -10 V, -15 V and -20 V, the approximate values of D_{eff} are 0.90 μm, 0.70 μm, 0 61 μm, 0 53 μm and 0 46 μm, respectively The reduction of D_{eff} affects the performance of the n-channel JFET.

The values of the drain current (I_D) and the transconductance (g_m) in this n-channel JFET are expressed as follows. In the linear region,

$$I_D = \frac{q\mu_n N_{\text{chan}} W D_{\text{eff}}}{L} \left\{ V_{DS} - \frac{2}{3}\sqrt{\frac{2\epsilon_0\epsilon_s}{qN_{\text{chan}}{D_{\text{eff}}}^2}} \times \left[(V_{DS} + V_{dg} - V_G)^{3/2} - (V_{dg} - V_G)^{3/2} \right] \right\} \quad (1)$$

and

$$g_m = \frac{\mu_n W}{L}\sqrt{2q\epsilon_0\epsilon_s N_{\text{chan}}} \left[(V_{DS} + V_{dg} - V_G)^{1/2} - (V_{dg} - V_G)^{1/2} \right], \quad (2)$$

where q is the charge of an electron, μ_n is the electron mobility, V_{DS} is the voltage between the source and the drain, ϵ_0 is the permittivity in vacuum, ϵ_s is the dielectric constant for silicon, and V_G is the voltage between the source and the gate. In the saturation region,

$$I_D = \frac{1}{3} \cdot \frac{q\mu_n N_{\text{chan}} W D_{\text{eff}}}{L} (V_p + V_{dg}) \left[1 - 3\left(\frac{V_{dg} - V_G}{V_p + V_{dg}}\right) + 2\left(\frac{V_{dg} - V_G}{V_p + V_{dg}}\right)^{3/2} \right] \quad (3)$$

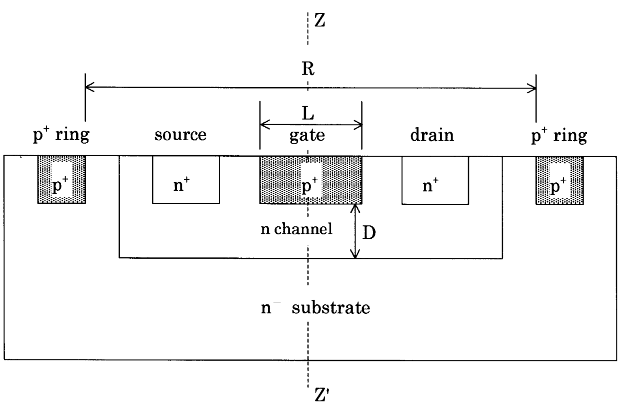

Fig. 2. Schematic cross section of a new structure of an n-channel JFET.

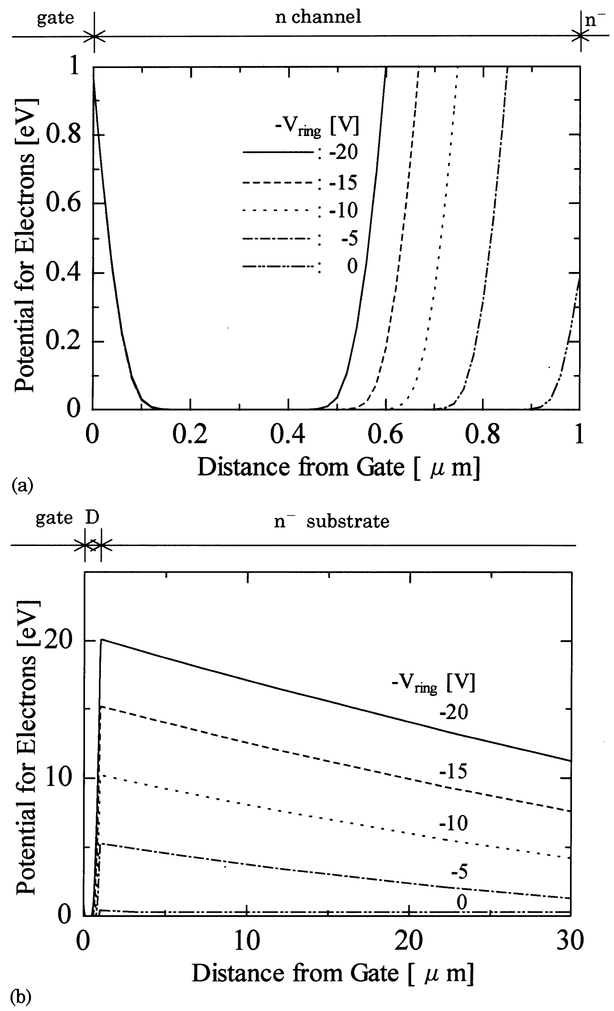

Fig. 3. Electron potential corresponding to various V_{ring}.

and

$$g_m = \frac{q\mu_n N_{\mathrm{chan}} W D_{\mathrm{eff}}}{L}\left[1-\sqrt{\frac{2\epsilon_0\epsilon_s\,(V_{\mathrm{dg}}-V_G)}{qN_{\mathrm{chan}}{D_{\mathrm{eff}}}^2}}\right], \qquad (4)$$

where V_p is the pinch-off voltage expressed by

$$V_p = \frac{qN_{\mathrm{chan}}{D_{\mathrm{eff}}}^2}{2\epsilon_0\epsilon_s} - V_{\mathrm{dg}}. \qquad (5)$$

Since D_{eff} is changed by V_{ring} as shown in Fig. 3(a), V_p can be controlled by V_{ring}. In Fig. 3(a), for example, the value of D_{eff} is about 0.46 μm at $-V_{\mathrm{ring}} = -20$ V. At $V_{DS} = 12$ V, $V_G = 0$ V and $-V_{\mathrm{ring}} = -20$ V using $\mu_n = 1200$ cm^2/V/s, the JFET is operated in the linear region because V_{DS} is lower than V_p of 15 V. At room temperature, I_D and g_m are 48 mA and 7.2 mS, respectively.

Since the values of I_D and g_m increase with μ_n, a high μ_n is required. In the n-channel JFET proposed here, high mobility could be expected at low temperatures, because the density of the ionized donor in the channel is much lower than the total density of the ionized donor and the ionized acceptor in the channel shown in Fig. 1(a).

3. An X-ray Pin Diode with the Proposed JFET

X-ray pin diodes consist of the n$^-$ substrate between a thin p$^+$ layer and a thin n$^+$ layer. Although the areas of the p$^+$ and n$^+$ layers are usually enlarged in order to widen the area of X-ray irradiation, the capacitance of the X-ray pin diode becomes large. In order to speed up the response of the X-ray pin diode, the capacitance of the X-ray pin diode should be reduced.

The schematic structure of the X-ray detector with the n-channel JFET proposed here is shown in Fig. 4. In order to reduce the capacitance of the X-ray pin diode, the area of the n$^+$ layer is reduced. The high negative bias voltage ($-V_{\mathrm{X\text{-}ray}}$) is applied to the p$^+$ layer of the X-ray pin diode to form the depletion region over the whole i layer. To effectively collect electrons produced by X-rays at the n$^+$ region due to the electric field, a p$^+$ ring is formed at the surface and the negative bias voltage ($-V_{\mathrm{ring}}$) is applied to the p$^+$ ring under the condition of $V_{\mathrm{X\text{-}ray}} > V_{\mathrm{ring}}$.

The n-channel JFET proposed here is located in the p$^+$ ring, as shown in Fig. 4. By applying $-V_{\mathrm{ring}}$ to the p$^+$ ring, the n channel is electrically separated from the n$^-$ substrate, as discussed in § 2.

As shown in Fig. 5, the n$^+$ layer of the X-ray pin diode is electrically connected to the gate of the JFET. When electrons produced by an X-ray flow into the n$^+$ layer of the X-ray pin diode, the voltage of the n$^+$ layer is lowered, indicating that the gate is more reverse-biased. Therefore, the drain current of the JFET can be accurately controlled by a small number of electrons produced by an X-ray.

In order to accomplish the rapid discharge of electrons collected at the n$^+$ layer of the X-ray pin diode before the electrons produced by next X-ray reach the n$^+$ layer of the X-ray pin diode, a pin diode for discharging electrons (referred to as a discharge pin diode) shown in Figs. 4 and 5 is introduced, as mentioned by Lechner *et al.*[7] When a small bias voltage (V_{dis}) is applied to the discharge pin diode, the voltage of the n$^+$ layer of the X-ray pin diode becomes slightly lower than V_{dis}, because the discharge pin diode should be slightly forward-biased and the X-ray pin diode and the pin

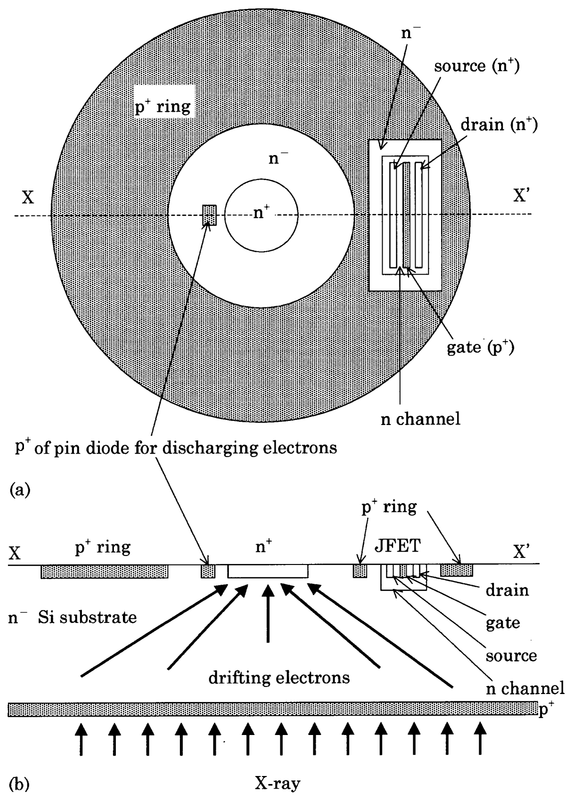

Fig. 4. Schematic structure of an X-ray pin diode with the n-channel JFET proposed here; (a) top view and (b) cross section.

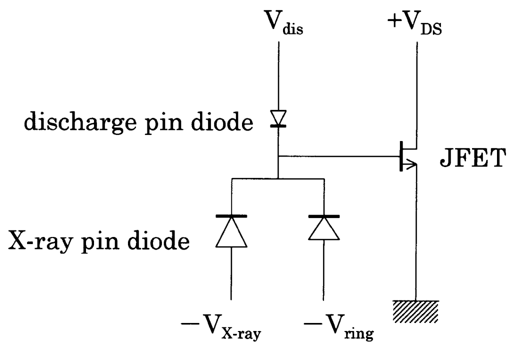

Fig. 5. Schematic electric circuit of the X-ray detector.

diode formed by the p$^+$ ring should be highly reverse-biased in order to balance the forward current of the discharge pin diode with the small reverse currents of the other pin diodes. Therefore, the operating gate voltage of the JFET can be controlled by V_{dis}. Since the discharge pin diode is more forward-biased when electrons produced by an X-ray are collected at the n$^+$ layer of the X-ray pin diode, the electrons can be discharged quickly from the n$^+$ layer through the discharge pin diode.

As mentioned above, the n-channel JFET proposed here is suitable for the integration on the X-ray detector chip.

4. Summary

We have proposed a new structure of an n-channel JFET embedded in an X-ray pin diode and have discussed the characteristics of this n-channel JFET. The n-channel JFET can be fabricated in the n^- substrate, without a p region under the n channel. Since the n channel of the JFET is doped with only one type of impurity, the high performance due to high mobility and the low noise characteristic due to the low defect densities could be expected. The fabrication of this n-channel JFET and the integration of the JFET on the X-ray detector chip are in progress.

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1) See, for example, Nucl. Instrum. & Methods in Phys. Res. **A377** (1996) 346.
2) R. Hartmann, D. Hauff, S. Krisch, P. Lechner, G. Lutz, R. H. Seitz, L. Strüder, G. Bertuccio, L. Fasoli, C. Fiorini, E. Gatti, A. Longoni, E. Pinotti and M. Sampietro: Technical Dig. Int. Electron Devices Meet., San Francisco, 1994, p. 535.
3) V. Radeka, P. Rehak, S. Rescia, E. Gatti, A. Longoni, M. Sampietro, G. Bertuccio, P. Holl, L. Strüder and J. Kemmer: IEEE Electron Device Lett. **10** (1989) 91.
4) K. Kandiah and F. B. Whiting: Nucl. Instrum. & Methods in Phys. Res. **A326** (1993) 49.
5) P. Lechner, L. Andricek, N. Findeis, D. Hauff, P. Holl, J. Kemmer, P. Klein, G. Lutz, N. Meidinger, E. Pinotti, R. Richter, L. Strüder and C. V. Zanthier: Nucl. Instrum. & Methods in Phys. Res. **A326** (1993) 284.
6) G. Bertuccio, L. Fasoli, C. Fiorini, E. Gatti, A. Longoni, M. Sampietro, D. Hauff, J. Kemmer and R. Richter: Nucl. Instrum. & Methods in Phys. Res. **A377** (1996) 352.
7) P. Lechner, S. Eckbauer, R. Hartmann, S. Krisch, D. Hauff, R. Richter, H. Soltau, L. Strüder, C. Fiorini, E. Gatti, A. Longoni and M. Sampietro: Nucl. Instrum. & Methods in Phys. Res. **A377** (1996) 346.