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Field-Induced Junction in InSb Gate-Controlled Diodes

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InSb gate-controlled diodes were fabricated to study breakdown behavior and surface effects. *I–V* characteristics were measured as a function of gate voltage and temperature. The results indicated that a field-induced junction was formed as the negative bias exceeded -4 V. The field induced junction was found to have a breakdown voltage smaller than that of the metallurgical junction. Saturation of the breakdown current in the field-induced junction was also observed, which could be explained by the conducting channel effect similar to that in the metal oxide semiconductor field effect transistor (MOSFET). The reverse current was also measured as a function of temperature to study the leakage mechanism. The strong exponential temperature dependence suggested that the reverse current was dominated by the G-R mechanism.

KEYWORDS: field-induced junction, InSb gate-controlled diode

InSb photodiodes are known to have large reverse leakage currents originating from the surface,[1-3] where the metallurgical junction meets the insulator-semiconductor interface. Proper surface passivation is usually required to minimize the leakage current in order to achieve good device performance. Another method for controlling the surface leakage is using the so-called gate-controlled diode structure. In this structure, surface potential is controlled by applying proper external bias voltage to the insulated gate metal deposited above the junction perimeter. Practically speaking, gate-controlled diodes are quite cumbersome when used as photodiodes, but they are excellent tools for the study of surface leakage. This is because the surface leakage can be measured as a function of the gate bias, and thus one can easily determine whether surface passivation is sufficient for suppressing the surface leakage. Fujisada and Kawada[2] studied the temperature dependence of reverse current in Be ion-implanted InSb gate-controlled diodes. A large leakage current originating from the surface was identified, suggesting that the junction breakdown occurred at the surface. They also found that generation-recombination (G-R) was the dominant mechanism for reverse current occurring in the metallurgical junction when the surface effect was suppressed by proper gate biasing. Similar studies were also performed by Adar, Nemirovsky and Kidron.[3] Their results indicated that breakdown occurred in the bulk and that band-to-band tunneling was the dominant mechanism in the reverse current.

Recently, high-quality InSb junction diodes with a breakdown voltage exceeding 14 V and an R_0A product of $1.2\times10^6\ \Omega\cdot\mathrm{cm}^2$ have been reported.[4] Studies on the surface effects of these diodes have become very important as they may provide information for understanding the breakdown behavior and leakage current mechanism. In this letter, we report on InSb gate-controlled diodes, the junction and passivation of which are formed by the same method as those for the high-quality InSb diodes mentioned above. *I–V* characteristics as a function of gate voltage are measured to study the surface effects. A field-induced junction in parallel with the metallurgical junction is clearly observed as the negative gate bias exceeds -4 V. The field-induced junction is found to have a breakdown voltage of its own, which is substantially lower than the breakdown voltage of the metallurgical junction. This result confirms that the breakdown of the high-quality diodes mentioned above must have occurred in the bulk, not at the surface. The temperature dependence of the gate diodes at zero bias was also studied and generation-recombination was found to be the dominating mechanism.

The junction of the gate controlled diodes was formed by Cd diffusion utilizing a two-temperature-zone method[5] with the Cd source at 380°C and the InSb substrate at 440°C. The substrates used have a carrier concentration of $N_D=1\times10^{14}\ \mathrm{cm}^{-3}$ at 77 K. A mesa structure with the dimensions of 0.4 mm × 0.85 mm was first etched by a mixture of 10:1 lactic/nitric acids. The passivation included anodic oxidation in a 0.1 N KOH solution for 5 minutes at a current density of $5\times10^{-4}\ \mathrm{A/cm}^2$ and a layer of 1500 Å evaporated SiO. Chromium of 600 Å was used for the gate metallization, which was evaporated above the SiO layer and completely covered the junction perimeter. A second layer of SiO with a thickness of ~1500 Å was deposited to bury the gate metallization. Contact windows for the gate and junction were then opened by a plasma etcher, followed by a Cr–Au metallization for contacts. A schematic cross section of the device is shown in Fig. 1. All temperature-dependent *I–V* measurements were made in a closed-cycle refrigerator.

Figures 2(a) and 2(b) show the *I–V* characteristics at 77 K in a 77 K background illumination. The gate bias voltage was varied from -10 to $+6$ V with 2 V increments. It is noted first that the qualities of these gate-

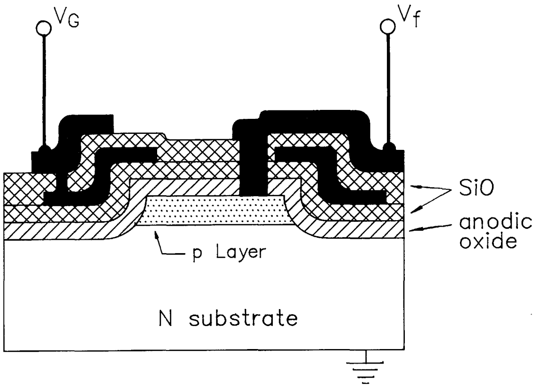

Fig. 1. Cross section of the gate-controlled diode.

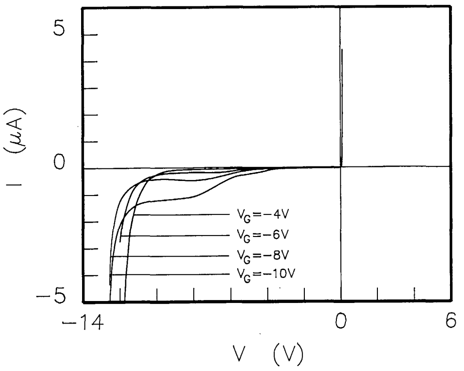

Fig. 2(a) *I–V* characteristics of the gate diode at 77 K as gate bias varies from −10 V to −4 V with 2 V increments.

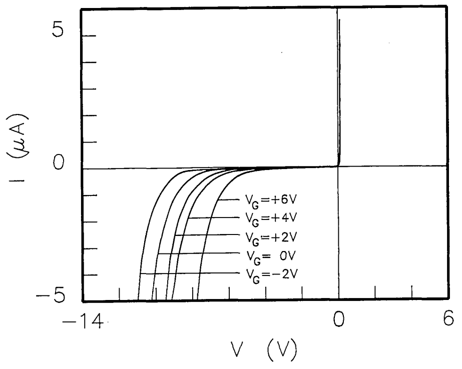

Fig. 2(b). *I–V* characteristics of the gate diode at 77 K as gate bias varies from −2 V to +6 V with 2 V increments.

controlled diodes at zero bias are very similar to those mentioned above,[4)] with a relatively high breakdown voltage exceeding 10 V and an R_0A product of $10^6\ \Omega\cdot\text{cm}^2$. It can also be seen in Fig. 2(a) that the reverse currents are almost independent of the gate voltage in the reverse voltage region from 0 to roughly 3 V. Since the reverse bias is greater than 3 V, the current shows a strong dependence on the gate bias. As the negative gate voltage exceeds −4 V, the current begins to increase drastically and then becomes saturated until breakdown occurs at a much higher voltage. The reverse saturation current is found to increase with the negative gate voltage. The breakdown voltage also becomes higher as the gate voltage is made more negative. It is believed that all of these interesting *I–V* characteristics are observed for the first time in InSb gate-controlled diodes, and these experimental observations can be explained qualitatively as follows.

As the gate voltage is made more negative than −4 V, a field-induced junction in parallel with the metallurgical junction must have formed under the gate as a result of surface inversion by the negative gate bias. This field-induced junction is usually very shallow and will break down at some voltage which is lower than the breakdown voltage of the the metallurgical junction. As the reverse voltage exceeds the breakdown voltage of the field induced-junction (roughly 3 V in the present case), current begins to flow along the inversion layer to the diffused p^+ region. This current will then saturate with a further increase in reverse voltage. The saturation characteristics observed in the field-induced junction can be explained by the conducting channel effect[6)] similar to that in metal oxide semiconductor field effect transistors (MOSFET). The saturation current level is also known to depend on the conductance of the conducting channel formed in the inversion region.

Figure 3 plots the breakdown voltage as a function of the gate voltage. The breakdown voltage is defined as the voltage when the reverse current reaches 5 μA. The dependence of breakdown voltage on the gate voltage can also be explained as follows. For positive gate bias, a field induced junction will be formed over the p^+ region, instead of over the n-substrate (see Fig. 1). This field-induced junction region is very narrow and tends to have a relatively higher electric field than the rest of the junction; thus junction breakdown will occur at a lower reverse bias voltage. On the other hand, as the gate

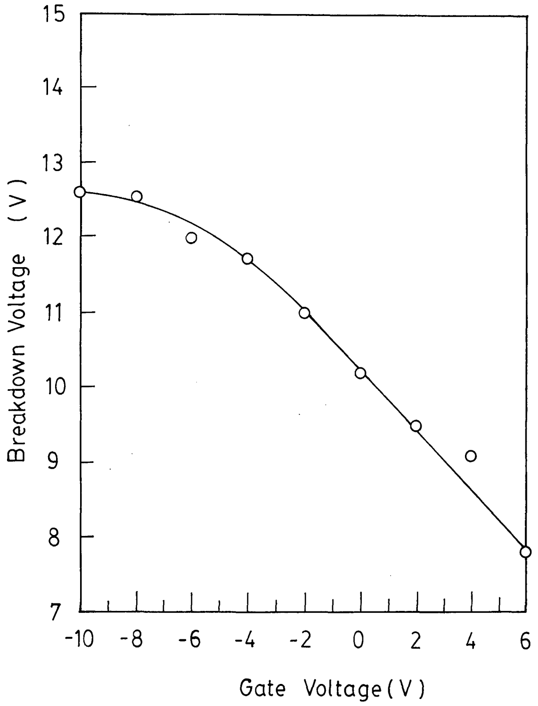

Fig. 3. Breakdown voltage of the gate diode as a function of the gate voltage.

voltage is made more negative than -4 V, a field-induced junction extending out into the n-type substrate is formed. The depletion region in the corner of the substrate is actually wider and will have a lower electric field, and thus a higher breakdown voltage. It ought to be noted that the field-induced junction in this case can have its own breakdown voltage which is lower than the breakdown voltage of the metallurgical junction and that the current through the field-induced junction will saturate due to the channel effect, as has been explained earlier.

Figure 4 shows the I-V characteristics of the gate diode at various temperatures with zero gate voltage. The reverse current is seen to increase drastically as the temperature is raised. It is well understood that tunneling-induced currents usually have a rather weak temperature dependence, while generation-recombination (G-R) currents have an exponetial temperature dependence. The strong temperature dependence shown in Fig. 4 suggests that the reverse current in the present diode is dominated by the G-R mechanism, rather than the tunneling.

In Fig. 5, we plot the reverse current against $E_g(T)/kT$ for $V=-0.6$ V and -2.4 V, where $E_g(T)$ is the bandgap of InSb and k is Boltzmann's constant. $E_g(T)$ in eV is known to be approximated by $E_g=0.247-0.078\times(T/300)$[7,8] in the temperature range from 77 K to 300 K. It can be seen that for both $V=-0.6$ V and -2.4 V, the reverse currents can be expressed as $I\propto\exp(E_g(T)/nkT)$, with the value n indicated in the figure. The n value is close to 2 for $T<130$ K and close to 1 for $T>130$ K. This result is expected and can be explained as follows. It is known from basic semiconductor physics that the generation and diffusion currents, the major two contributors to reverse current, have similar $I\propto\exp(E_g/nkT)$ temperature dependence with $n=2$ for the generation current and $n=1$ for the diffusion current.[8] Consequently, the generation current will dominate in the lower temperature range and the diffusion current will dominate in the higher temperature range. The present data suggest that the transition temperature from the generation current to the diffusion current is roughly 130 K.

In conclusion, InSb gate-controlled diodes were fabricated and a field-induced junction was clearly observed when the negative gate bias exceeded -4 V. Saturation of the channel current in the field-induced junction was also observed. Breakdown voltage of the metallurgical junction was found to increase as the negative gate voltage was increased. It was also concluded from the temperature dependence of the reverse current that generation-recombination, instead of tunneling, is the dominant mechanism. The result is consistent with that of Fujisada and Kawada[2] but contradicts that of Adar *et al.*[3] It is suspected that the different conclusions concerning the dominating current mechanism might be due to the use of different carrier concentration substrates, $N_D=2\times10^{14}$ cm^{-3} by Fujisada and Kawada[2] and the present authors, and $N_D=2\times10^{15}$ cm^{-3} by Adar *et al.*[3] Further investigation on the reverse characteristics with respect to substrate carrier concentration for InSb junction diodes will be needed in order to resolve the controversy.

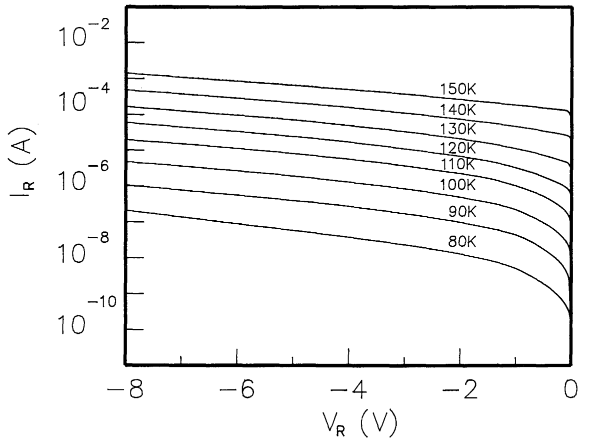

Fig. 4. I-V characteristics of the gate diode as the temperature varies from 80 K to 150 K with 10 K increments.

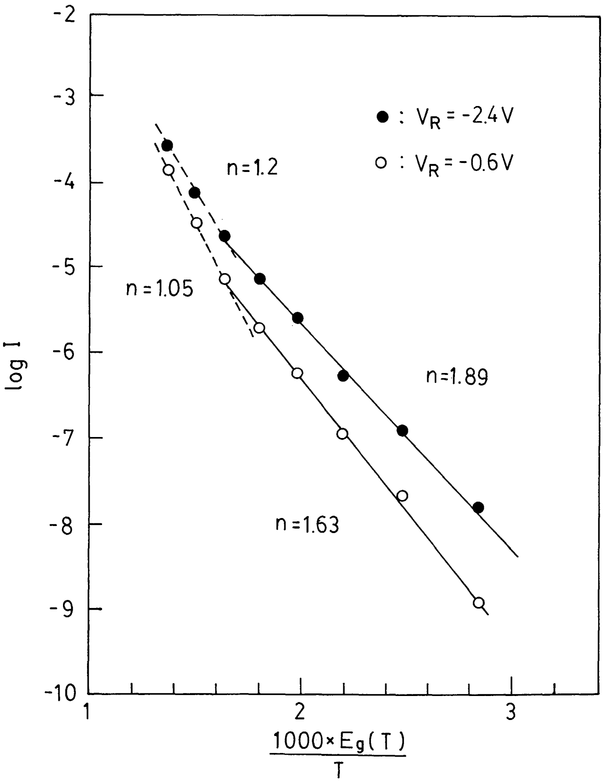

Fig. 5. Reverse current of the gate diode against $100E_g(T)/T$ for $V_R=-0.6$ V and $V_R=-2.4$ V.

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