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New Measurement Technique for Sub-Bandgap Impact Ionization Current by Transient Characteristics of Partially Depleted SOI MOSFETs

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We have developed a novel, sensitive measurement technique for the sub-bandgap impact ionization current in scaled metal-oxide-semiconductor field effect transistors (MOSFETs). In this technique, partially depleted silicon on insulator MOSFETs is utilized where the floating body potential is gradually charged by the impact ionization current. The transient increase of the body potential causes a decrease in the threshold voltage due to the body effect, resulting in a transient increase in the drain current. The impact ionization current is derived from the transient increase in the body potential. The derived impact ionization current is in good agreement with the direct current measurement. Furthermore, the new measurement technique is very sensitive even in the sub-bandgap region and measurements of less than 50 fA are demonstrated.

KEYWORDS: MOSFET, sub-bandgap impact ionization, silicon on insulator, transient measurement, floating body effect, partially depleted SOI

1. Introduction

Recently, impact ionization has been observed in short channel metal-oxide-semiconductor field effect transistors (MOSFETs) at a drain voltage of less than 1.1 V, which corresponds to the bandgap energy of silicon.[1–3] The impact ionization in this region is called sub-band-gap impact ionization. This sub-bandgap impact ionization affects the device reliability of very scaled MOSFETs operating at very low voltages. Therefore, it is essential to elucidate the mechanisms of the sub-bandgap impact ionization phenomena. Simulations results of the mechanism have been reported.[4,5] However, the sub-bandgap impact ionization current is generally so small that no experimental results have been reported on the mechanisms.

In this paper, we report a novel, sensitive measurement technique for the sub-bandgap impact ionization current using the transient characteristics of partially depleted (PD) silicon on insulator (SOI) MOSFET. The derived impact ionization current is in good agreement with the directly measured impact ionization current. The sensitivity is less than 50 fA, which is better than that of the direct measurements.

2. New Measurement Technique

The device used is a 0.13 μm SOI MOSFET with a single drain structure.[3] The device, fabricated on a separated-by-implanted-oxygen (SIMOX) substrate, has body contacts on both sides. The thickness of the gate oxide, SOI layer and buried oxide are 5.0 nm, 100 nm and 100 nm, respectively. The poly-Si gate is defined by electron beam lithography. The SOI device is in fully depleted (FD) mode when the substrate bias V_{sub} is set to 0 V, while the device is changed to the PD mode when a negative V_{sub} (−12 V) is applied. Figure 1 shows a schematic diagram of the device and circuit. For the direct body current measurement, the body terminal is connected to the source. For the transient measurement, the body terminal is released from the circuits and the potential of body region is floats.

Figure 2 shows the body current, which is measured directly. The well-known bell-shaped current curves indicate that the body current is caused by the impact ionization. It should be noted that the sub-bandgap ionization current is

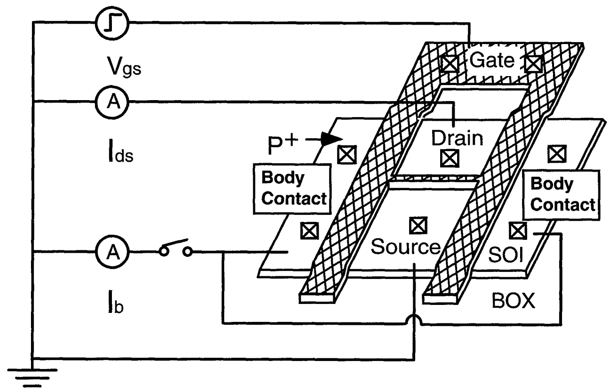

Fig. 1. A schematic view of a partially depleted (PD) SOI MOSFET with a single drain structure. The device fabricated on a SIMOX substrate has body contacts on both sides. The thicknesses of the gate oxide, SOI layer and buried oxide are 5.0 nm, 100 nm and 100 nm, respectively.

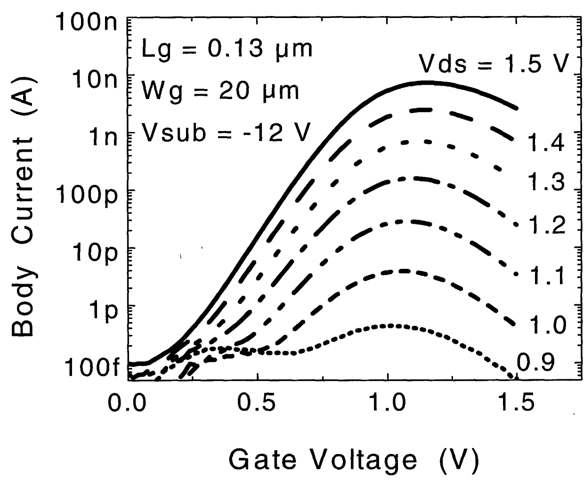

Fig. 2. The body current measured directly as a function of gate voltage at different drain voltages in the PD SOI MOSFET. The body current is due to the impact ionization current, which is well known as a bell-shaped current. The sub-bandgap impact ionization is clearly observed at drain voltages below 1.1 V.

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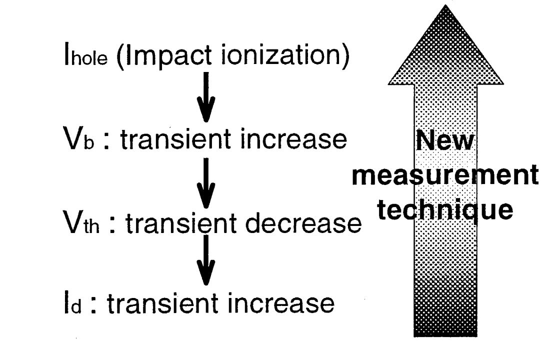

Fig. 3. The principle of the new measurement technique. In PD SOI MOSFETs, the impact ionization current charges the body potential, causing a transient increase in the drain current. The new measurement technique makes use of the relationship among the impact ionization current, body potential and drain current.

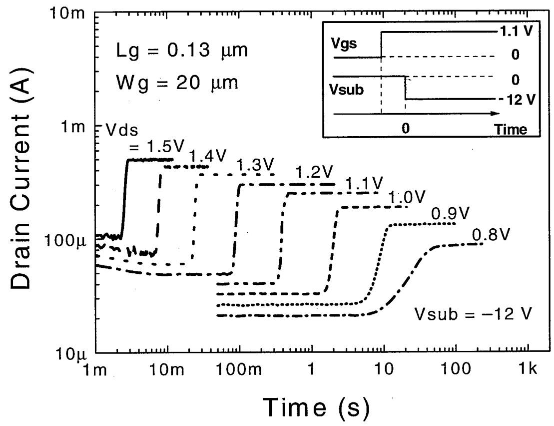

Fig. 4. The transient drain current at various drain voltages after the step voltages are applied to the gate and the substrate. As the drain voltage decreases, the time constant of transient current increases exponentially. The inset shows the sequence of the voltage applications.

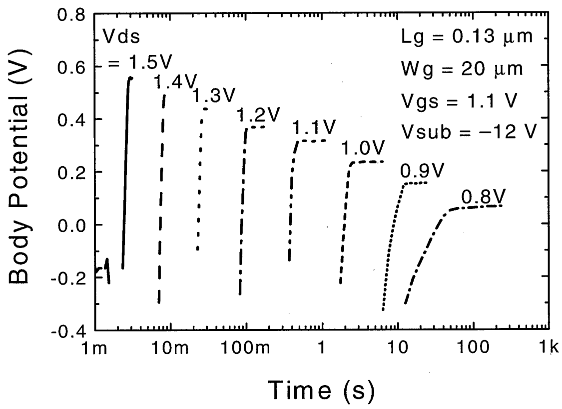

Fig. 5. The transient change in the body potential derived from the transient increase in the drain current in Fig. 4. The dependence of the drain current on body potential was measured in advance.

clearly observed at drain voltages below 1.1 V. The current cannot be measured below 0.9 V due to the limit of the direct current measurements.

In the PD SOI MOSFETs, the impact ionization current charges the potential of the body region, causing a transient decrease in the threshold voltage. Consequently, the drain current increases gradually as shown in Fig. 3. The new measurement technique makes use of this relationship among the impact ionization current, body potential and drain current. In the reverse way, the impact ionization current could be estimated from transient characteristics of drain current. The conventional direct measurement method for impact ionization current is limited by the sensitivity of current measurements as mentioned above. However, the proposed technique is more sensitive because the transient drain current is far above the sensitivity limit.

3. Results and Discussions

When a step voltage is applied to the PD SOI MOSFET, a transient increase or decrease in the drain current is observed depending on the interplay between the body potential increase due to the impact ionization current and the hole redistribution inside the body region.[3] As mentioned above, the impact ionization current causes a transient increase in the drain current. However, when a step voltage is applied the body potential increases immediately, because the depletion layer expands suddenly and confines the excess holes in the floating body region. Then the body potential falls down as the holes redistribute. Therefore, a transient decrease of the drain current is observed by hole redistribution. To increase the accuracy of the measurements of the impact ionization current, the effects of the hole redistribution must be eliminated. The inset of Fig. 4 shows the sequence of the step voltage applications to the gate and the substrate. When the step gate voltage is applied, the V_{sub} remains at 0 V. Hole redistribution takes place immediately because the device is in the FD mode where the excess holes can easily escape to the source. Then the step substrate bias (−12 V) is applied. Because hole redistribution is already over and the device is in the PD mode, only the potential increase due to impact ionization is observed.

Figure 4 shows the transient drain current at various drain voltages after the step voltage is applied. The step gate voltage is 1.1 V. The transient time constant changes exponentially with the drain voltage. This result is explained by the increase in the impact ionization current as the drain voltage increases. Figure 5 shows the transient changein the body potential derived from the transient increase in the drain current as shown in Fig. 4. The body bias dependence of the drain current was measured in advance. The impact ionization current can be derived from dV_{body}/dt using the following equation:

$$I_{body} = C\frac{dV_{body}}{dt} \tag{1}$$

where C is the capacitance connected to the body. When the body potential is around 0 V, the body current corresponds to the impact ionization current. However, when the body potential increases, the body/source junction is positively biased and the current to the source also contributes to I_{body}. Therefore, the slope of the line in Fig. 5 should be determined around the value $V_{body} = 0$.

Figure 6 compares dV_{body}/dt near the zero bias with the body current (impact ionization current). The square symbols corresponds to the body current in the vertical axis measured directly at $V_{body} = 0$. On the other hand, dV_{body}/dt in the horizontal axis is derived from the transient measurements in Fig. 5. It should be noted that they correlate well and that

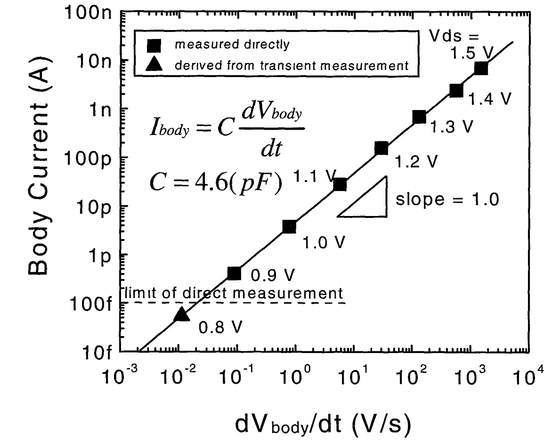

Fig. 6. The relation between $dV_{\rm body}/dt$ and body current (impact ionization current). Squares indicate body current, which is measured directly. The triangle indicates the derived impact ionization current, which is less than the sensitivity of the direct measurements.

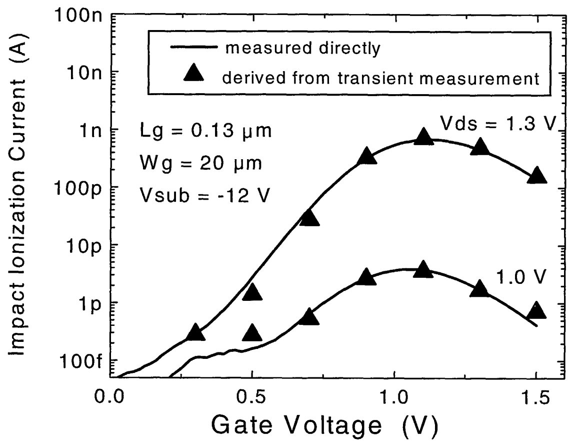

Fig. 7. The impact ionization currents measured by this technique (triangles) and directly (solid lines). These measurements are in good agreement on both below and above the bandgap energy of silicon.

the slope is unity. This indicates that the impact ionization current is accurately derived from the transient measurements and that this technique is very reliable and precise. From Fig. 6, the capacitance C is estimated to be 4.6 pF, which corresponds to the sum of the body capacitance and the pad capacitance.

The triangle in Fig. 6 indicates the derived impact ionization current at a drain voltage of 0.8 V, which is less than the limit of the direct measurements. The sensitivity is better than the direct measurements and is less than 50 fA. Figure 7 compares the impact ionization current measured by this technique (triangles) and directly (solid lines). The well-known bell-shaped curves are accurately measured by only the transient measurement. This technique can be applied to floating PD MOSFETs where the body potential is around 0 V. We can also estimate the impact ionization current of PD MOSFETs with increased body potential using the assumption that the floating device has approximately the same impact ionization ratio ($I_{\rm body}/I_{\rm d}$) as the tied device.[6] This sensitive measurement technique will be very effective for investigating the mechanisms of sub-bandgap impact ionization.

4. Conclusions

A novel, sensitive measurement technique for sub-bandgap impact ionization current of scaled MOSFETs has been developed. The impact ionization current is derived from the transient measurement of PD SOI MOSFET and is in good agreement with the direct current measurement. The sensitivity is less than 50 fA, which is better than that of the direct measurements.

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