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Temperature effect on impact ionization characteristics in metamorphic high electron mobility transistors

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Recently, the metamorphic high electron mobility transistors, MHEMTs (InP based layers on GaAs substrate), have attracted considerable attention for high power and low noise microwave applications. From the physical point of view, the increased gate leakage current as well as decreased breakdown voltage are mainly caused by the carrier generation within the channel and carrier transport across the Schottky barrier layer. Thus, the carrier generation through effective impact ionization in channel layer is responsible for the breakdown characteristics.

Since the impact ionization is inversely proportional to the bandgap value, the narrow bandgap of InGaAs channel makes it susceptible to induce the impact ionization effect. This problem usually leads to the deteriorated device characteristics including the low breakdown voltage, high gate leakage current, and high output conductance. The extraction of impact ionization-induced gate current from the total measured gate current becomes essential to study the impact ionization effect. It is noticeable that the impact ionization effect strongly depends on the Schottky barrier height of gate contacts. The adequate determination of gate metals can suppress the impact ionizations and then improve the device characteristics. In this work, the temperature-dependent characteristics of gate-metals-related impact ionizations in MHEMTs are investigated. Different metals, including Pt/Au, Ti/Au, and Au, as the Schottky gate contacts are fabricated simultaneously to study the impact ionization effects. In order to consider the impact ionization-induced gate current, the convenient excess gate hole current model established by Webster et al. is employed. Besides, two distinct mechanisms (ionization threshold energy and hot electron population) for impact ionization, which separately dominate in different field ranges, are also presented to interpret the anomalous electric field and temperature dependences. For comparison, gate Schottky contacts were achieved by evaporating Pt/Au (20nm/130nm), Ti/Au (20nm/130nm), and Au (150 nm), three kinds of different metals, for devices A, B, and C, respectively, on the Schottky barrier layer by using the same process sequence.

Figure 1 shows the schematic band diagrams and calculated electron densities within channel layer regimes at thermal equilibrium. Due to the increase of Schottky barrier height, the electron concentrations are decreased for devices A and B. Hence, the generation of electron-hole pairs and related impact ionization effect are effectively suppressed. The presence of large conduction band discontinuity (ΔE_C) between InAlAs Schottky and InGaAs channel layers also substantially suppresses electrons injecting into the gate. This certainly further improves the carrier confinement capability at higher temperature. The measured common-source I-V characteristics at different temperatures are illustrated in Fig. 2. It should be noted that the kink effects or other degenerative behaviors caused by the impact ionization are not observed in studied devices among the temperature of 300 ~ 480K. In particular, for device A, the drain current ID is not compressed significantly even the V_{GS} is increased up to +0.5 V. Furthermore, the device A shows the relatively lower drain-source saturation current I_{DSS}. This is because that the Pt/Au gate metals (device A) lead to the increase of Schottky barrier height. This may considerably extend the depletion region beneath the gate and result in the reduced I_{DSS}.

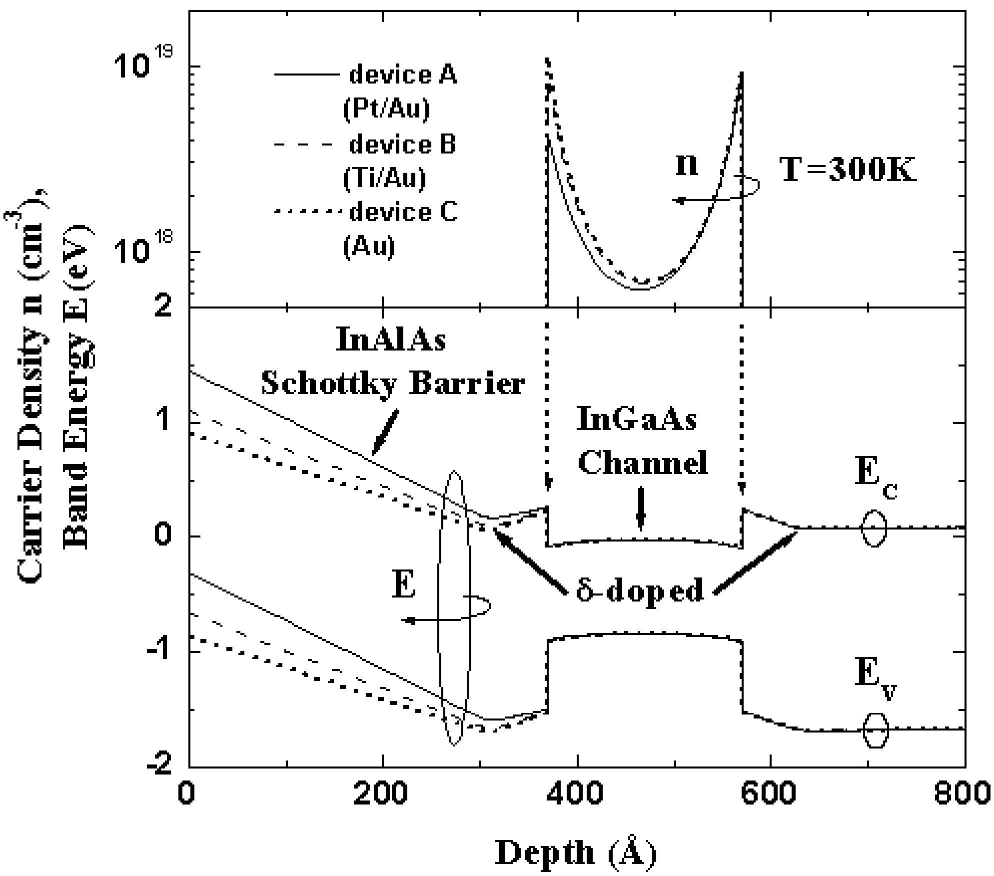

Fig. 1 Schematic band diagrams and calculated electron densities within channel layer regimes of the MHEMTs with different Schottky gate metals.

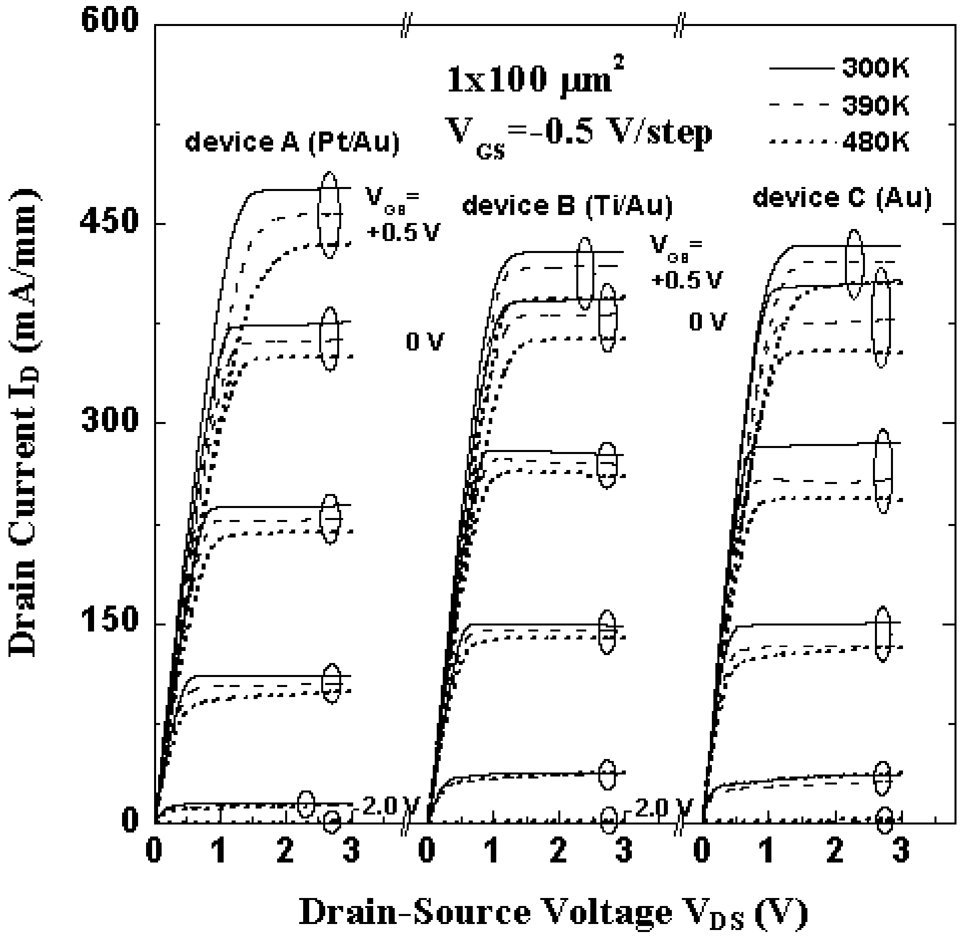

Fig. 2 Typical common-source I-V characteristics at different temperatures.

Figure 3 shows the total gate current (I_G) and impact ionization-induced gate current ($I_{G,ii}$) versus gate-source voltage (V_{GS}) under different electric field (V_{DS}) at 300K. Also, the evolutions of I_G and $I_{G,ii}$ versus V_{GS} under high electric field (V_{DS} = +2.0 V), at 300 ~ 480K, are shown in Fig. 4. Clearly, the bell-shaped behavior reflects the preponderance of the impact ionization at high V_{DS} and low temperature over the Schottky gate leakage current. The existence of bell-shaped behavior is caused by the impact ionization which requires both the conditions of significantly high electron concentration and high electric field. At moderate $|V_{GS}|$ regimes, the electron-hole pairs are generated in the high electric field region between the gate and drain electrodes. Also, a portion of holes are injected across the Schottky layer and collected by the gate terminal. Therefore, the gate hole current and related bell-shaped behavior are increased and occurred simultaneously, as indicated in Figs. 3 and 4. The total gate current is composed of the hole current component, due to impact ionization occurring in the channel, and the Schottky leakage current component. According to the gate hole current model, the $I_{G,ii}$ can be expressed as:

$$I_{G,ii} = I_G - I_{G,Schottky} \quad (1)$$

where $I_{G,Schottky}$ is the Schottky gate leakage current which is a function of both the gate and drain voltage. Clearly, the bell-shaped behaviors, caused by the impact ionizations, of devices A and B are significantly suppressed as compared with that of device C. This is caused by the evaporation of specific gate contacts, *e.g.*, Pt/Au and Ti/Au. These higher Schottky barrier heights will lead to the substantial change of potential energy. This indeed extends the channel depletion region beneath the gate and results in the decrease of drain current in the channel. Therefore, the impact ionization effect can be effectively suppressed. Especially, it is found that the peak $I_{G,ii}$ of devices A and B shift toward more positive V_{GS} regimes over wide operating temperature ranging from 300 to 480K, as shown in Fig. 4. Due to the increased phonon scattering with increasing the temperature, the electron mobility and drain current are decreased. Hence, because the peak $I_{G,ii}$ is dominated by the drain current density under the identical electric field, the $|V_{GS}|$ magnitudes of devices A and B are needed to decrease to maintain the same drain current density.

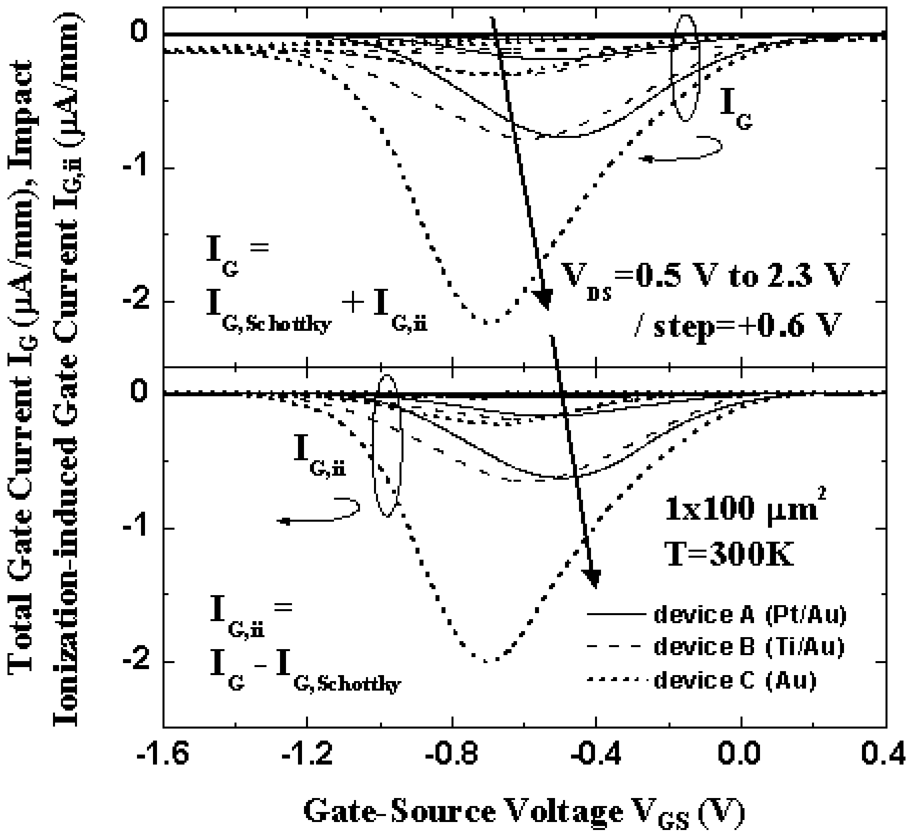

Fig. 3 The total gate current (I_G) and impact ionization-induced gate current ($I_{G,ii}$) versus gate-source voltage (V_{GS}) under different drain-source voltage (V_{DS}) at room temperature.

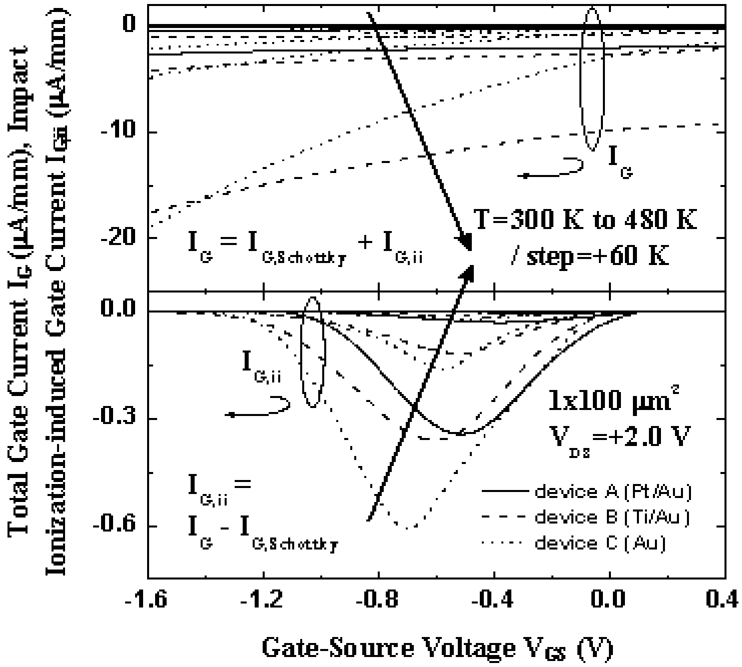

Fig. 4 The total gate current (I_G) and impact ionization-induced gate current ($I_{G,ii}$) versus gate-source voltage (VGS) at different temperatures.

The corresponding reverse evolutions of $I_{G,ii}$ between the electric field (V_{DS}) and temperature dependences are observed. This indicates that the electric field and temperature dependences of impact ionization mechanisms are different. Thus, it is important to understand and determine the dominant mechanism in different field regimes. Practically, the electric field and temperature dependences of impact ionization in device operation are mainly determined by the competition between the ionization threshold energy and hot electron population. As shown in Fig. 3, with the decrease of the electric field (lower V_{DS} bias), the impact ionization is dominated by the high ionization threshold energy. Because electrons are distributed under relatively cool status, the hot electron population is substantially reduced at low electric field. This leads to the absence of impact ionization in the channel as well as the reduced $I_{G,ii}$. In contrast, since the high electric field is presented in gate-drain region at high V_{DS} bias, electrons acquire enough energies and the hot electron-assisted impact ionization is easy to take place in channel layer. Subsequently, the related electron-hole pairs are generated which lead to the increase of $I_{G,ii}$. On the other hand, as shown in Fig. 4, once the temperature is increased from 300 to 480K, the ionization threshold energy and related bandgap are slightly decreased which tend to enhance the impact ionization effect. However, the mean free paths of channel electrons are significantly decreased due to the increased phonon scattering. This indicates that the lattice electrons are hard to be released with the insufficient energy. Thus, the hot electron population and the corresponding impact ionization are substantially suppressed though the ionization threshold energy is slightly decreased. Simultaneously, an overall decrease of $I_{G,ii}$ with increasing the temperature is observed.

In conclusion, the gate-metals-related impact ionizations in MHEMTs have been investigated. The influences of Schottky barrier height on the impact ionization effect and device performance are also studied. Further, two distinct mechanisms, which separately dominate the impact ionization in different field regimes, are proposed to interpret the anomalous electric field and temperature dependences. As a result, by using the higher Schottky barrier height of gate metals, both the bell-shaped behavior and related impact ionization effect are significantly suppressed. Also, the impact ionization-induced gate current is decreased with reducing the electric field and/or increasing the temperature.