Enhanced Schottky barrier on InGaAs for high performance photodetector application

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A low temperature (LT = 77 K) processing technique was used for Schottky metal deposition on InGaAs. The Schottky barrier height of Ag/InGaAs contact processed at low temperature was found to be 0.64 eV. This value is more than two times higher than that of the barrier height of 0.30 eV obtained from the sample processed at room temperature (RT). The enhanced Schottky contacts are superior for the application on high performance semiconductor photodetectors. The current–voltage–temperature (I–V–T) measurements were conducted to study the current transport mechanism. Atomic force microscope was used to study the surface morphology correlating with the electrical properties. The LT metal showed cracked structure, which combined by islands, while the RT metal surface appeared to be more uniform with some sharp dots. © 1998 American Vacuum Society. [S0734-2101(98)52803-5]

I. INTRODUCTION

Metal-semiconductor-metal photodetectors (MSM PDs) have attracted considerable interest in recent years due to high speed, low capacitance per unit area, and ease of incorporation in optoelectronic integrated circuit receivers.1–3 An important consideration in the design of InGaAs based MSM PDs for the optical communication application in the wavelengths of 1.3 and 1.55 μm is the metal/semiconductor Schottky contact. However, the Schottky barrier height to InGaAs is very low (about 0.2–0.3 eV) which results in a large dark current. The conventional method to increase the metal/InGaAs Schottky barrier height is employing a very thin cap layer above InGaAs active layer, such as InP, InAlAs, GaAs, and AlGaAs,4–7 as a barrier-enhancement layer. The device high frequency performance could be degraded due to the carrier trapping in the band edge discontinuity. It was also reported that an additional layer of insulating Si₃N₄ could further reduce the dark current. From a processing point of view, any of the additional layers certainly increase the technology complexity. In this article, a low temperature (LT = 77 K) processing was used for Schottky metal deposition on InGaAs. The Schottky barrier height of Ag/InGaAs contact processed at low temperature was found to be 0.64 eV. This value is more than two times higher than that of the sample processed at room temperature with barrier height of 0.30 eV. The dark current density was reduced by more than four orders in magnitude by LT processing. This will greatly increase the signal-to-noise ratio of the MSM device while maintaining the high-speed performance. As confirmed by consistent results from different substrates and Schottky metals, the LT processing provides a simple and efficient approach to obtain high performance MSM photodetectors.

II. EXPERIMENT

The sample used in this work was molecular beam epitaxy grown InGaAs on InP substrate. The n-type (undoped) epitaxial InGaAs was 3 μm thick lattice matched to a S-doped n-type InP substrate. The doping level in the epilayer is about 1 × 10¹⁶ cm⁻³. Sample was cleaned by organic solutions and DI H₂O before metal deposition. Ohmic contact was formed by thermal evaporation of AuGe and Ni layers, and the subsequent annealing. The metal deposition was carried out in an Edwards Auto-306 system. Before Schottky metal deposition, the sample surface was etched in a H₂SO₄ based solution to remove the natural surface oxidation. Schottky metal Au or Ag was deposited through a shadow mask with the semiconductor substrate at room temperature (RT) or LT. The detail of the low temperature deposition was described elsewhere. The low temperature deposition of metal to semiconductor has been successfully used to fabricate high quality Schottky contacts on InP, InGaAs, and AlGaAs. The most important characteristics of the LT formed Schottky contact, are the significantly increased Schottky barrier height, reduced reverse leakage current, and low metal layer resistivity. The long-term stability of LT processing has also been demonstrated. The temperature dependent current–voltage–temperature characteristics (I–V–T) were tested by a HP4140 meter, and carried out in a cryogenic system with data auto acquisition at temperatures ranging from 50 to 300 K.

III. RESULTS AND DISCUSSIONS

Figure 1 showed the I–V characteristics of the Ag/InGaAs contact fabricated at LT and RT. The LT processed sample showed more than four order lower reverse leakage current. The device performance strongly depends on the Schottky metal deposition temperature. The RT Ag/InGaAs...
diode behaved almost as an Ohmic contact, which showed the very high reverse leakage current, and the very low barrier height. The barrier height $\phi_B$ was calculated by using the following relation,

$$J_0 = A^* T^2 \exp(-\phi_B/kT),$$  \hspace{1cm} (1)

where $J_0$ is the saturation current density at zero bias, and $A^*$ is the effective Richardson constant of the $n$-InGaAs. The ideality factor, $n$, is defined as

$$n = (q/kT)[\partial V/\partial (\ln J_0)].$$  \hspace{1cm} (2)

The barrier height, $\phi_B$, obtained from the RT Ag/InGaAs was about 0.30 eV, with ideality factor, $n$, far deviated from unit. For the Ag/InGaAs contact processed at LT, the barrier height was 0.64 eV, with an ideality factor of 1.06. For comparison, Au metal was also chosen for LT processing. The obtained barrier height was about 0.60 eV, with an ideality factor of 1.32. Both Ag and Au on InGaAs processed at LT showed barrier heights much higher than those of conventional room temperature processed Schottky contacts. The barrier height obtained by LT processing showed significant reduced reverse leakage current (four to five orders in this work). Since in a MSM photodetector, the signal-to-noise ratio is inversely proportional to the dark current, the enhanced Schottky contact with high barrier height and low reverse leakage current would be superior for the application of MSM photodetectors.

To further study the current transport mechanism of the InGaAs Schottky contacts, $I-V-T$ measurements were carried out at temperatures ranging from 50 to 300 K. Figure 2 showed the $I-V-T$ plots from a RT processed Ag/InGaAs Schottky diode. Figure 3 showed the $I-V-T$ plot from a LT processed Ag/InGaAs Schottky diode. The difference between the RT and LT diodes is obvious. For the RT diode, the forward characteristics did not show any linear zone. The extraction of barrier height from the plot according to Eqs. (1) and (2) was an estimation, but not an accurate result. The ideality factor, $n$, could not be obtained from such a nonlinear plot. The plots of $I-V-T$ for the RT diodes showed, however, zones with different current transport mechanism. In lower bias region, the current decreased with the decreasing of temperature, the plots themselves were still nonlinear. So this region could be a thermal emission (TE) dominant zone combined with high excess current. The forward current exhibits a saturation trend at the high forward bias region. In this region, the current showed temperature independent and deviation from the TE theory. This indicated that the transport mechanism in this region was controlled by thermionic field emission or purely field emission. Figure 4
showed the $I-V-T$ plots from an LT Au/InGaAs Schottky diode. It still showed a TE dominated conduction mechanism with strong temperature dependence.

Figures 5 and 6 were the images from atomic force microscope (AFM) measurements for the RT and LT deposited Schottky contact surfaces. The roughness analysis for each sample was also shown in Figs. 5 and 6. The rms were 6.550 nm and 7.633 nm in a 10 μm scan for LT and RT samples, respectively. Previous study was carried out for the thin metal films deposited at RT and LT at very thin thickness (less than 100 Å).13 It was found that the LT film became conducting at much thinner thickness than the same metal deposited at RT. Also the thin LT metal films were usually rougher in the beginning due to the formation of many islands. These islands extended in two dimensions and eventually showed smoother surface. While the RT films showed smoother in the beginning since it started with small spots, and then extended in three-dimension. The RT film showed rougher as it grows thicker. In this study, the Schottky metal film thicknesses for LT and RT are both about 1000 Å, which is much thicker than the films in our previous study. It can be seen that the RT film showed overall smoother surface morphology with some sharp spots. The LT films look rougher, and consist of cracked structures. It is believed that these cracked structures are the continuation of the small island formed at LT observed with thinner thickness. In thin film study, the formation of island structure in the early stage leads to the low resistivity of LT films.13 It is possible that the lower resistivity enlarged the work function difference.
between the metal and semiconductor, so a higher barrier height could be achieved. For the Schottky contact formation, however, much more complicated mechanism would be involved especially for the metal/InGaAs interface. Further evidences are needed to correlate the LT film with the current transport mechanism.

IV. CONCLUSIONS

High barrier height Schottky contact in InGaAs was obtained by low temperature deposition of metal Ag and Au. The current transport mechanism showed strong processing temperature dependence. The room temperature processed contact showed thermal emission in low bias region, and field emission at higher biased region, while the low temperature processed contacts showed thermal emission dominated transport mechanism only. The best LT Ag/InGaAs contacts showed a barrier height $\phi_B$ of 0.64 eV, and a significantly reduced reverse leakage current. Such an enhanced barrier height will be superior for a MSM photodetector application where low dark current is critical for a high performance device.

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