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Photoresponse of the $In_{0.3}Ga_{0.7}N$ metal–insulator–semiconductor photodetectors*

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$In_{0.3}Ga_{0.7}N$ metal–insulator–semiconductor (MIS) and metal–semiconductor (MS) surface barrier photodetectors have been fabricated. The $In_{0.3}Ga_{0.7}N$ epilayers were grown on sapphire by metalorganic chemical vapour deposition (MOCVD). The photoresponse and reverse current–voltage characteristics of the $In_{0.3}Ga_{0.7}N$ MIS and MS photodetectors were measured. A best zero bias responsivity of 0.18 A/W at 450 nm is obtained for the $In_{0.3}Ga_{0.7}N$ MIS photodetector with 10 nm Si_3N_4 insulator layer, which is more than ten times higher than the $In_{0.3}Ga_{0.7}N$ MS photodetector. The reason is attributed to the decrease of the interface states and increase of surface barrier height by the inserted insulator. The influence of the thickness of the Si_3N_4 insulator layer on the photoresponsivity of the MIS photodetector is also discussed.

Keywords: InGaN, photodetector, metal–insulator–semiconductor structure
PACC: 7480G, 7340N

The III–V nitride alloy systems are of outstanding current interest for a wide range of device applications, including blue and green light-emitting diodes (LEDs) and laser diodes (LDs), ultraviolet photodetectors, high-temperature and high-power field effect transistors, etc.[1−5] $In_xGa_{1-x}N$ superlattice and quantum well have been used as active layers for these optoelectronic devices, such as LEDs and LDs. In 2002, Wu *et al* found that the bandgap energy of high-quality single crystalline InN is 0.7 eV, which is much smaller than previously reported 1.89 eV.[6] This means that the $In_xGa_{1-x}N$ ternary alloy system spans bandgaps continuously from 0.7 to 3.4 eV or wavelengths from 1771 to 365 nm, and thus provides a near-perfect match to the solar energy spectrum. This creates the opportunity to design and fabricate new solar cells with greatly improved efficiencies.[7,8] However, because of the large lattice mismatch (about 11%) and the large difference of the equilibrium vapour pressure of nitrogen between GaN and InN, the growth of high-quality thick $In_xGa_{1-x}N$ films (especially with high In fraction) is quite difficult.[9,10] Among the photovoltaic detectors, the photoresponse characteristic of p–n structure detectors is better than surface barrier structure detectors. However, p-doping technology for $In_xGa_{1-x}N$ is still under investigation. It is difficult at present to study p–n junction $In_xGa_{1-x}N$ photodetectors. In this paper, $In_{0.3}Ga_{0.7}N$ metal–insulator–semiconductor (MIS) and metal–semiconductor (MS) surface barrier photodetectors are designed and fabricated. The photoelectric response and reverse current–voltage characteristics of the photodetectors are measured and compared. The effect of thin insulator layer and influence of the thickness of insulator layer on the photoelectric response of $In_{0.3}Ga_{0.7}N$ MIS photodetector are discussed.

Samples used in this study were grown on c-face (0001) sapphire substrates by metalorganic chemical vapour deposition (MOCVD). The $In_{0.3}Ga_{0.7}N$/GaN samples consisted of a 30-nm-thick low-temperature GaN buffer layer, a 2 μm-thick high-temperature unintentionally doped GaN buffer layer, and a 200-nm-thick unintentionally doped n^--$In_{0.3}Ga_{0.7}N$ absorption layer. MIS photodetectors were fabricated on

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the surface-treated $In_{0.3}Ga_{0.7}N$ using a photolithographic technique. Figure 1 is the schematic diagram of the $In_{0.3}Ga_{0.7}N$ MIS structure photodetectors. The ohmic contacts were formed by using magnetron sputtered Ti/Al/Ni/Au (20 /30 /20 /50 nm) and then annealed at 600 °C for 1 min in N_2 atmosphere. The plasma-enhanced chemical vapour deposited (PECVD) Si_3N_4 was used as the insulator layer. The thicknesses of Si_3N_4 used in MIS structures were 5, 10 and 15 nm. Prior to fabrication of Schottky contacts, the sample surfaces were treated using organic solvent and acids. Ni was chosen as the Schottky contact metal because of its high power function, and 10-nm of which was sputtered onto the Si_3N_4 layer to form the MIS structure. Then a thick Au layer was deposited as the bonding pad. For comparison, MS structure photodetector without insulator layer was also fabricated using the same method. After the above processing, the samples were passivated with Si_3N_4.

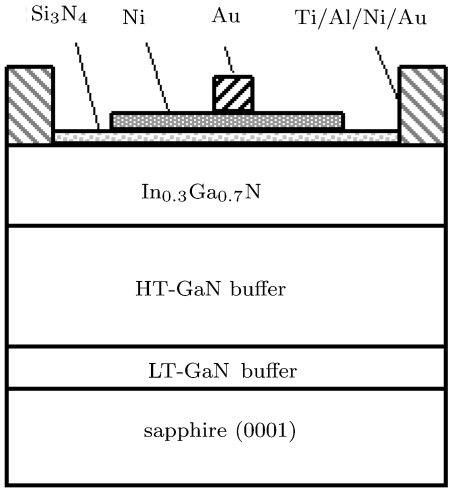


Fig.1. Schematic diagram of the $In_{0.3}Ga_{0.7}N$ MIS structure.

The characteristic of reverse current without illumination and photoelectric response of the MIS photodetector have been measured. Figure 2 is the reverse current–voltage curves of the $In_{0.3}Ga_{0.7}N$ photodetector with different thickness of Si_3N_4 insulator layers. As shown in Fig.2, the reverse current of the MS structure is larger than that of the MIS structures. The reverse current decreases with the increase of the Si_3N_4 thickness. The reverse current of the MS structure consists mainly of majority carrier thermal-electron-emission current and interface recombination current. In the $In_{0.3}Ga_{0.7}N$ MS structure, there is a large quantity of interface states and defects. A thin Si_3N_4 layer inserted between Ni and $In_{0.3}Ga_{0.7}N$ can increase the effective interface barrier height and thus decrease the thermal-electron-emission current; it also saturates part of the dangling bond in the interface and decreases the interface combination current. This can be explained by using the interfacial insulator model.[11] From this model, the barrier height φ_b can be written as

$$\varphi_b = \varphi_{b0} + \Delta\varphi, \tag{1}$$

$$\Delta\varphi = (2kT/\hbar)(2m\chi)^{1/2}\delta, \tag{2}$$

where φ_{b0} is the barrier height without the interfacial layer and $\Delta\varphi$ is the additional barrier due to the insulator; δ and χ are the thickness and the mean tunnelling barrier height of the insulator layer; k, T, m and $\hbar$ are Boltzmann's constant, temperature, tunnelling effective electron mass and the reduced Planck's constant. From the above expression, it can be seen that the insulator is efficient to improve the barrier height. The energy band diagrams at the interface of n^--InGaN/metal with or without an interfacial insulator layer are shown in Fig.3. This indicates clearly that the thermal electron emission is restrained by the increase of surface barrier.

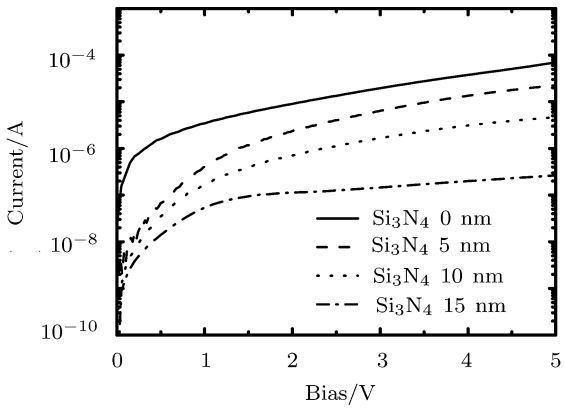


Fig.2. The reverse current–voltage curves of the $In_{0.3}Ga_{0.7}N$ photodetector measured without illumination.

The photoelectric responses of the $In_{0.3}Ga_{0.7}N$ MIS photodetector with four different thicknesses of Si_3N_4 layer under zero bias have been measured, the result of which is shown in Fig.4. The high responsivities of the four samples are observed from 300 to 450 nm, and sharp cut off can be seen at 450 nm. The zero bias photoelectric responses of the 5-nm Si_3N_4, 10-nm Si_3N_4, 15-nm Si_3N_4 MIS photodetectors and MS photodetector are 0.08 A/W, 0.18 A/W, 0.04 A/W and 0.016A/W at 450 nm, respectively.

When the thin Si_3N_4 layer is inserted, the photoelectric responses of the MIS photodetector are all increased. The direction of photo-generated current is opposite to the direction of the thermal electron emission. A Si_3N_4 insulator thin layer can increase the effective surface barrier height, decrease the thermal electron emission and thus weaken the loss of the photo-generated current. Furthermore, the Si_3N_4 insulator thin layer can decrease the density of the interface states between metal and semiconductor and thus decrease the loss of the photo-generated current.

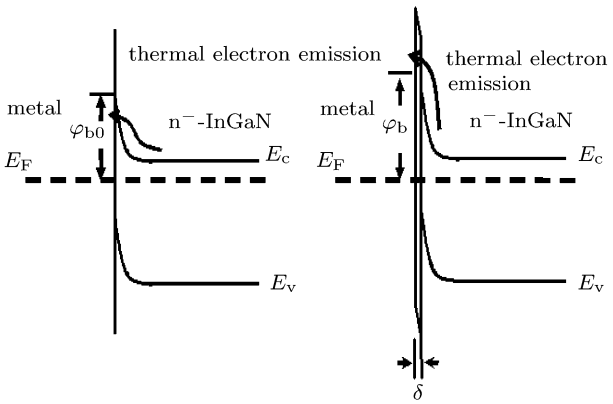


Fig.3. Energy band diagrams for n$^-$-InGaN/metal with or without an interfacial insulator layer.

It also can be seen from Fig.4 that the responsivity of the photodetector increases with the thickness of the Si_3N_4 layer. A best zero-bias responsivity of 0.18 A/W at 450 nm is obtained from the 10 nm-MIS structure, which is more than ten times larger than from the MS structures. However, when the thickness of the Si_3N_4 layer increases up to 15 nm, the responsivity can be seen to decrease. The photo-generated minority carriers in the valence band are collected mainly through thermal emission and tunnel. If the insulator is too thick, the tunnelling current will be restrained and leads to the decrease of the photo current. So, among the samples in this work, the best thickness of Si_3N_4 is 10nm.

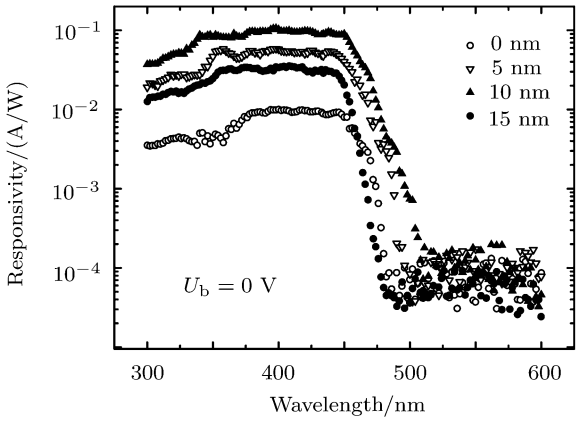


Fig.4. Photoresponse for $In_{0.3}Ga_{0.7}N$ MS and MIS photodetectors with different insulating layer thickness under zero bias.

In conclusion, $In_{0.3}Ga_{0.7}N$ epilayers have been grown on sapphire by MOCVD method. $In_{0.3}Ga_{0.7}N$ MS and MIS photodetectors with different thicknesses of Si_3N_4 insulator layer are fabricated. The photoelectric response and reverse current–voltage characteristics without incident light of the $In_{0.3}Ga_{0.7}N$ photodetectors are measured. The best zero bias photoelectric responsivity of the $In_{0.3}Ga_{0.7}N$ MIS photodetector with 10 nm Si_3N_4 insulator layer is 0.18A/W at 450 nm, which is more than ten times higher than that of $In_{0.3}Ga_{0.7}N$ MS photodetector. The reason is attributed to the increase of effective interface barrier height and the decrease of the interface states density by the inserted insulating thin layer.

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