InAs/GaP/InGaP high-temperature power Schottky rectifier

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An InAs/GaP/InGaP rectifier has been fabricated using a semiconductor-semiconductor ''Schottky'' junction to utilize the thermal stability of the semiconductor-semiconductor interface. The InAs/GaP/InGaP system demonstrates rectifying characteristics with an ideality factor of 2.3 and a current–voltage extracted barrier height of 0.96 eV. It exhibits low reverse bias leakage current and achieves breakdown electric field of 0.6 MV/cm. The InAs/GaP/InGaP system maintains the rectifying characteristics up to 600 °C. Further improvement of the thermal stability is expected to be achieved by reducing the diffusion of Si dopant atoms across the InAs/GaP interface at high temperature. [DOI: 10.1063/1.1711180]

InGaP has been widely studied for optoelectronic and high-speed devices. The InGaP/GaAs lattice-matched system has been applied in heterojunction bipolar transistor, metal-semiconductor field effect transistor, and high electron mobility transistor.[1–4] $In_{0.49}Ga_{0.51}P$, with a direct band gap of 2.0 eV, provides a visible wavelength operation for light-emitting diodes and laser diodes.[5,6] Due to its wide band gap, high mobility ($\sim$3000 cm^2/V s) and high breakdown electric field ($\sim$0.8 MV/cm), InGaP has received growing attention in the applications of high-temperature and high-power devices.[7,8] Semiconductor materials can be evaluated with the Baliga figure of merit (BFOM) for high-power applications as shown in Table I.[7,9] An important application of wide band gap materials is to make high-power rectifiers. InGaP has BFOM of 37 normalized to that of Si as 1, which means that an InGaP rectifier will have a theoretical mobility limited on-resistance 37 times less than that of a Si rectifier. Various metal/InGaP Schottky contacts have been studied for this application.[10–14] However, conventional metal-semiconductor Schottky rectifiers degrade at high temperature due to metal migration across the metal/semiconductor interface.[15] Since most power devices are inevitably subjected to heat treatment during processing or Joule heating caused by the current through the devices, thermal stability is a critical concern for power devices.

The idea of a semiconductor-semiconductor (S-S) ''Schottky'' rectifier was proposed in the study of the InAs/GaP heterojunction system.[16] Heavily doped InAs has room temperature mobility as high as 33 000 cm^2/V s and can be used as a ''metal'' layer on another semiconductor layer to form a Schottky contact. In spite of the large lattice mismatch ($\sim$11%) and high density of 90°-type dislocations, the InAs/GaP heterojunction has been shown to have nearly ideal Schottky diode current–voltage ($I-V$) characteristics.[16] It was discovered that the InAs/GaP heterojunction maintained the Schottky rectifier characteristics after heat treatment up to 700 °C.[17] This outstanding thermal stability is thought to be due to strong covalent bonding at the InAs/GaP interface. The InAs/GaP heterointerface effectively blocks impurity diffusion.

Since InGaP is superior to GaP for high-power applications, as shown by the BFOM in Table I, the InGaP S-S Schottky rectifier has been demonstrated by growing InAs on InGaP. The direct growth of InAs on InGaP produced a leaky diode, which is thought to be due to the In-rich interface between InAs and InGaP. In this work, to avoid the In-rich interface in the InAs/InGaP structure, a thin layer of GaP ($\sim$50 Å) was grown between InAs and InGaP. The InAs/GaP/InGaP structure utilizes both the high-temperature stability of the InAs/GaP interface and the properties of InGaP for high-power applications. The electrical characteristics and thermal stability of the InAs/GaP/InGaP system are reported in this letter.

The InAs/GaP/InGaP sample was grown by solid source molecular beam epitaxy. Figure 1 shows the sample structure. A 2.5-μm-thick 3×10^{-16} cm^{-3} silicon (Si) doped InGaP layer was grown lattice matched on a GaAs substrate with a heavily doped GaAs buffer layer between these two layers. The surface of the InGaP layer was compositionally graded to GaP through a 200-Å-thick layer, and was followed by a 50-Å-thick GaP layer. A 500-Å-thick 1×10^{20} cm^{-3} Si doped InAs layer was grown on top of the GaP layer. Finally a thin $In_{0.75}Al_{0.25}As$ capping layer (50 Å) was grown on top of the InAs layer to minimize the decomposition of InAs at high temperature. TiAu contact was deposited using e-beam evaporator and patterned using lift-off for electrical characterization. Schottky rectifiers were fabricated by etching InAs in $1H_2O_2:3H_3PO_4:50H_2O$ using the patterned TiAu as a mask. A backside ohmic contact was made of AuGeNi alloyed at 400 °C for 30 s in a rapid thermal annealer (RTA). No edge termination techniques were used. For comparison, a TiAu/InGaP metal-semiconductor

TABLE I. Material parameters for Si, GaAs, GaP, and InGaP and Baliga's figure of merit (BFOM) for Si, GaAs, GaP, and InGaP power devices.

Property	Si	GaAs	GaP	InGaP[a]
E_G (eV)	1.12	1.42	2.26	2.01
ε_r	11.9	13.1	11.1	11.75
E_{CR} (V/cm)	3×10^5	4×10^5	10×10^5	8×10^5
μ (cm^2/V s)	1500	8500	200	3000
BFOM (Si=1)	1	15	4	37

[a]With composition of 49% In and 51% Ga, and lattice matched to GaAs.

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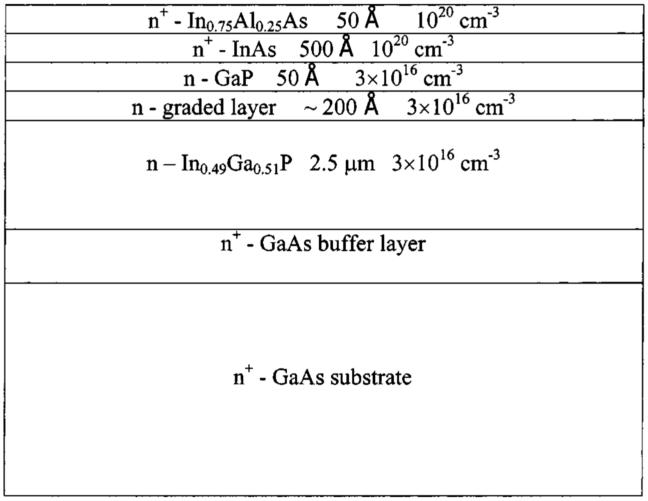

FIG. 1. Structure of the MBE sample for the InAs/GaP/InGaP Schottky rectifier.

rectifier was also made by etching off the top InAs/GaP layers, and evaporating TiAu directly on InGaP.

Current–voltage ($I-V$) characteristics were measured using a HP4156A parameter analyzer. The forward bias $I-V$ characteristics of the InAs/GaP/InGaP rectifier and the TiAu/InGaP rectifier are given in Fig. 2. The InAs/GaP/InGaP rectifier shows linear $I-V$ characteristics over seven orders of magnitudes of current on the semilogarithm scale. By fitting the $I-V$ characteristics to the thermionic emission-diffusion theory,[18] the ideality factor and the barrier height were calculated to be 2.3 and 0.97 eV, respectively. This barrier height is consistent with the reported barrier height between n-InAs and n-GaP.[16] The ideality factor of the InAs/GaP/InGaP rectifier (=2.3) is larger than that of an ideal Schottky diode (=1), and limits the on-current at higher forward bias. This nonunity ideality factor is probably caused by defects associated with the lattice-mismatched GaP/InGaP structure. To verify this assumption, three structures, metal/InGaP, metal/GaP/InGaP, and InAs/GaP/InGaP, were fabricated and

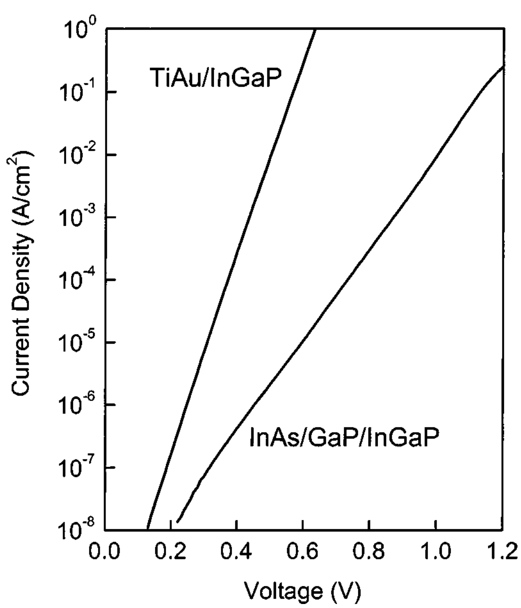

FIG. 2. The forward bias current–voltage characteristics of the InAs/GaP/InGaP rectifier and the TiAu/InGaP rectifier.

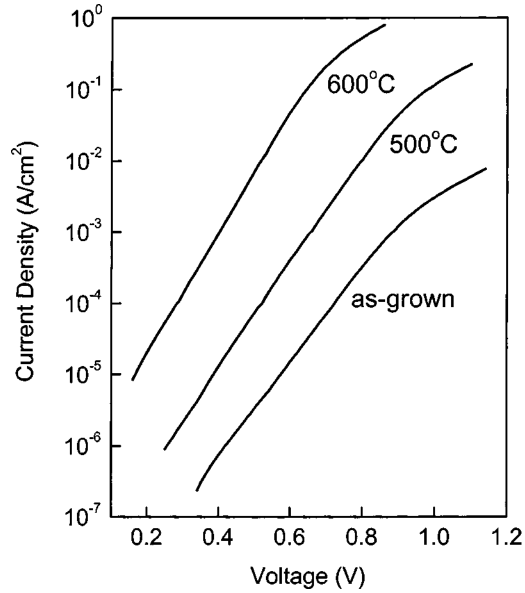

FIG. 3. The forward bias current–voltage characteristics of the InAs/GaP/InGaP rectifier after annealing at 500 and 600 °C in RTA for 1 min.

compared. The ideality factor of the metal/InGaP, metal/GaP/InGaP, and InAs/GaP/InGaP structures are 1.1, 2.0, and 2.3, respectively. The similar ideality factors of InAs/GaP/InGaP and metal/GaP/InGaP confirm that their nonunity ideality factors are related to the lattice mismatched GaP/InGaP system. The effect of the GaP/InGaP mismatched system may be minimized by reducing the thickness of the GaP and grading layers to enable direct tunneling. The InAs/GaP/InGaP rectifier shows low reverse leakage current density ($\sim 0.8 \mu A/cm^2$ at 0.3 MV/cm) and the breakdown voltage above 40 V. The maximum parallel plane electric field achieved is about 0.6 MV/cm for InAs/GaP/InGaP and 0.35–0.4 MV/cm for TiAu/InGaP.

The thermal stability of the InAs/GaP/InGaP rectifier was tested by annealing in a furnace and/or a RTA in N_2 ambient at temperatures from 300 to 600 °C, before the deposition of TiAu. Figures 3 and 4 are the forward bias and reverse bias current–voltage characteristics after annealing at 500 and 600 °C for 1 min in RTA. Silicon dioxide (SiO_2) cap layer was employed to minimize the decomposition of InAs during the annealing. The rectifiers show increased current after high-temperature annealing, but still maintain the

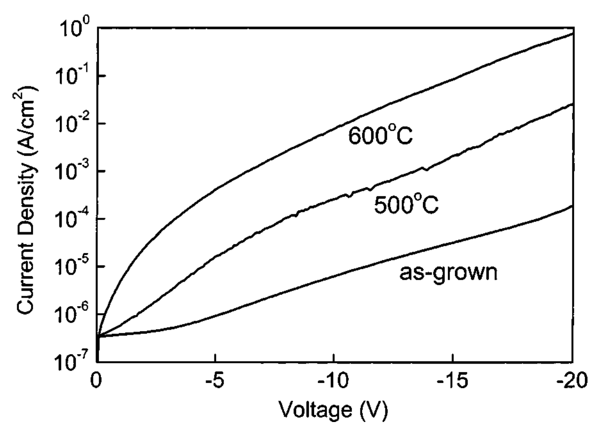

FIG. 4. The reverse bias current–voltage characteristics of the InAs/GaP/InGaP rectifier after annealing at 500 and 600 °C in RTA for 1 min.

Schottky rectifier characteristics up to 600 °C. The barrier height is 0.8 eV after 600 °C annealing. The lower barrier height after annealing at high temperatures explains the increased current. In comparison, the TiAu/InGaP rectifiers become less rectifying after annealing at 300 °C.

The changes after 600 °C annealing are thought due to the diffusion of the Si dopant atoms across the InAs/GaP interface, which makes the junction less abrupt. Electrochemical capacitance–voltage was employed to measure the carrier concentration before and after annealing. The result shows that after annealing the carrier concentration in the InAs layer decreases and the carrier concentration in the GaP/InGaP layer increases. This result indicates the diffusion of Si dopant atoms across the interface. Device failure due to Si diffusion across the interface was also observed in the InAs/GaAs and InAs/GaP systems previously studied. A lighter doping in the InAs layer may help to reduce Si diffusion.

In summary, the InAs/GaP/InGaP structure exhibits the electrical characteristics of a Schottky rectifier, with low reverse leakage current and high breakdown voltage. It maintains the rectifying characteristics after heat treatment up to 600 °C. The diffusion of Si dopant atoms across the interface is observed at high temperature. Further improvement on the thermal stability may be achieved by employing a lightly doped InAs or undoped InAs layer at the interface.

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