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High voltage GaInP/GaAs dual-material Schottky rectifiers

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A dual-material structure of lattice-matched GaInP on GaAs has a calculated figure of merit which is approximately 60 times better than Si and 5 times better than GaAs. In this work, the theoretical performance of the GaInP/GaAs structure is presented and experimental data for Ni on GaInP/GaAs Schottky rectifiers is presented. The Ni on GaInP/GaAs Schottky rectifiers have a breakdown voltage of ~80 V and low reverse leakage current. Comparable Ni on GaAs Schottky rectifiers have a breakdown voltage of ~20 V and significantly higher reverse leakage current. The GaInP/GaAs rectifiers' forward characteristics have a current–voltage extracted ϕ_{Bn} of 1.0 eV with an ideality factor of 1.06. This dual-material structure of GaInP/GaAs appears to be a promising candidate for improving power device performance.
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Power semiconductor device applications have been identified as an important research area for wide band-gap materials and devices.[1] Vertical power devices have been traditionally fabricated using a single material such as Si or GaAs.[1] Most studies have compared the power device properties of single semiconductor materials and analyzed the tradeoffs of using Si and compound semiconductor materials,[2] while the concept of using a dual material has not been investigated in detail. A candidate dual-material structure is lattice-matched GaInP on GaAs. The idea of using a GaInP/GaAs dual-material structure is based on the premise of placing a high critical field material layer on top of a high mobility material layer. The objective of the dual-material structure is to reduce power dissipation by minimizing the device on-resistance. The device on-resistance is lowered by either increasing the epilayer doping, decreasing the epilayer thickness, or selecting a material with a high mobility (the maximum epilayer doping and minimum epilayer thickness are a function of the material critical field and the required breakdown voltage). A GaInP/GaAs dual-material structure leverages both the high critical field of GaInP and the high mobility of GaAs. The structure is designed such that the highest electric fields are supported in the GaInP and the GaInP layer is thick enough so the electric field is less than the critical field of GaAs at the GaInP/GaAs interface. The critical field of GaInP is approximately twice that of GaAs, so the optimal material thickness for each layer, assuming uniform doping, is about half the total thickness. Drawings of the dual-material GaInP/GaAs structure and the electric field distribution are given in Fig. 1. The effective mobility of the GaInP/GaAs structure is a weighted average of the mobilities of GaInP and GaAs.

In addition to the issues of critical field and carrier mobility, the conduction band offset of the dual-material interface must be considered. A significant conduction band offset will result in an additional series resistance component which may offset the advantages realized by utilizing the high mobility material layer. n-type GaInP on n-type GaAs abrupt heterojunctions have been shown to have a conduction band offset which affects current transport.[3] The GaInP/GaAs conduction band offset has been measured to be about 0.22–0.25 eV.[4,5] The experimentally measured values are slightly larger than the theoretical calculations of the conduction band offset for ordered GaInP (0.13 eV) and disordered GaInP (0.12).[6] While the conduction band offset of the GaInP/GaAs interface is not large, it may be necessary to grade the interface and possibly add a delta-doped layer to reduce conduction band offset effects.

The mobility limited on-resistance of a vertical power device can be expressed in terms of the required blocking voltage and semiconductor properties:

$$R_{\mathrm{ON}}=\frac{4V_B^2}{\varepsilon_s\mu_n E_{\mathrm{CR}}^3} \tag{1}$$

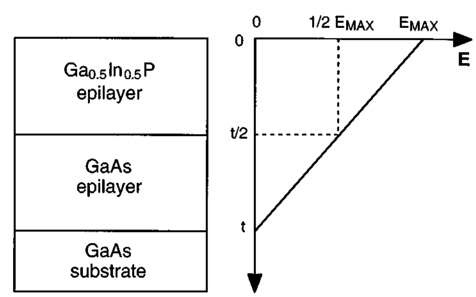

FIG. 1. Dual-material GaInP/GaAs structure and a graph of the structure's electric field distribution at the critical electric field.

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TABLE I. Table of material parameters for GaAs, GaInP, and dual-material GaInP/GaAs and Baliga's figure of merit (BFOM) for GaAs, GaInP, and dual-material GaInP/GaAs power devices.

Property	GaAs	GaInP	GaInP/GaAs
E_G (eV)	1.43	2.01	N/A
ϵ_r	13.1	11.75	N/A
E_{CR} (V/cm)	4×10^5	8×10^5	8×10^5 [a]
μ (cm^2/V s)	8500	3000	5750[a]
Calculations			
BFOM (GaAs=1)	1	2.5	4.9

[a]Effective numbers for an ideal material structure.

where R_{ON} is the on-resistance, V_B is the blocking voltage, ϵ_s is the dielectric constant, μ_n is the electron mobility, and E_{CR} is the critical field.

Semiconductor materials may be compared by using a figure of merit developed by Baliga[7] [Baliga's-figure-of-merit (BFOM)] which is the denominator of the on-resistance equation. The BFOM has been calculated for GaAs, GaInP, and GaInP/GaAs and is given in Table I, along with the materials parameters used in the calculations.[8,9] The BFOM calculations for GaAs, GaInP, and GaInP/GaAs show that the GaInP/GaAs structure has a figure of merit which is approximately 5 times larger than GaAs. Therefore, an ideal GaInP/GaAs structure will have a theoretical mobility limited on-resistance which is 5 times less than the minimum mobility limited on-resistance of GaAs. In addition, the GaAs interface has a high density of surface states that pin the surface Fermi level to midgap while the GaInP interface is known to have a significantly lower density of surface states.[11] Therefore, the GaInP interface allows for greater variability of metal-semiconductor barrier heights (important for power Schottky rectifiers) and lower surface leakage current.

A GaInP/GaAs sample and a GaAs reference sample were grown by molecular beam epitaxy (MBE) in a solid-source GEN-II MBE system. The GaInP/GaAs sample has a 1.5-μm thick, 1×10^{16} cm^{-3} doped n-type GaInP epilayer grown on top of a 1.25-μm thick, 1×10^{15} cm^{-3} doped n-type GaAs epilayer (an ideal structure would have equal epilayer thicknesses and doping). The GaAs sample has a 3-μm thick, 2×10^{16} cm^{-3} doped n-type epilayer. Both samples were grown on heavily doped n-type GaAs substrates. Schottky rectifiers were fabricated by liftoff patterning of circular Ni contacts. Large area backside contacts were formed by mounting the samples with indium. No edge termination techniques were used. Device diagrams for both the GaInP/GaAs sample and the GaAs sample are given in Fig. 2.

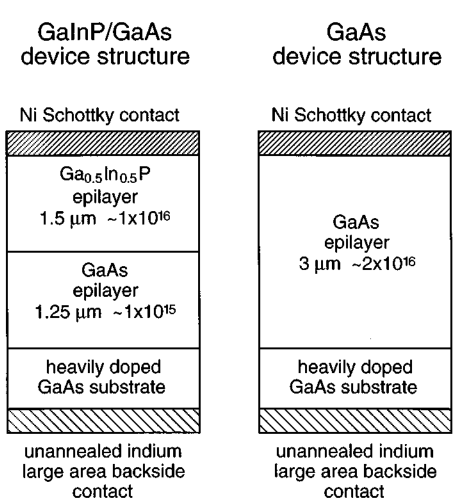

FIG. 2. Device structure for Ni dual-material GaInP/GaAs Schottky rectifiers and Ni GaAs Schottky rectifiers.

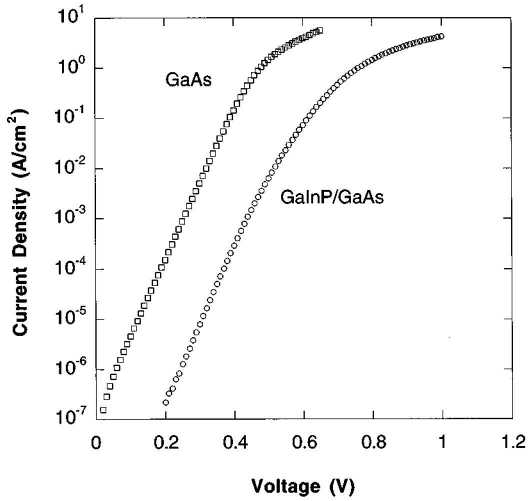

FIG. 3. Forward bias current–voltage characteristics of Ni dual-material GaInP/GaAs Schottky rectifiers and Ni GaAs Schottky rectifiers.

Current–voltage ($I-V$) and capacitance–voltage ($C-V$) characteristics were performed by directly probing individual devices. $I-V$ characteristics were measured using an HP 4145 parameter analyzer and $C-V$ characteristics were measured using an HP 4274 LCR meter.

The forward bias $I-V$ characteristics of Ni Schottky rectifiers on the GaInP/GaAs sample and the GaAs sample are given in Fig. 3. The GaInP/GaAs devices have an ideality factor of 1.06 and a ϕ_{Bn} of 1.0 eV. The GaAs devices have an ideality factor of 1.10 and a ϕ_{Bn} of 0.84 eV. These results are in agreement with reported Ni GaAs Schottky rectifier results of an ideality factor of 1.05 ± 0.05 and a ϕ_{Bn} of 0.85 ±0.05 eV.[10] The GaInP/GaAs devices show a substantially

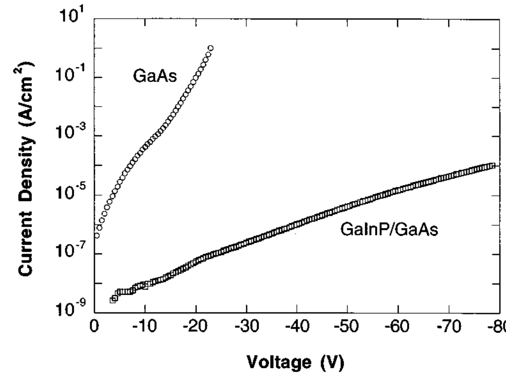

FIG. 4. Reverse bias current–voltage characteristics of Ni dual-material GaInP/GaAs Schottky rectifiers and Ni GaAs Schottky rectifiers.

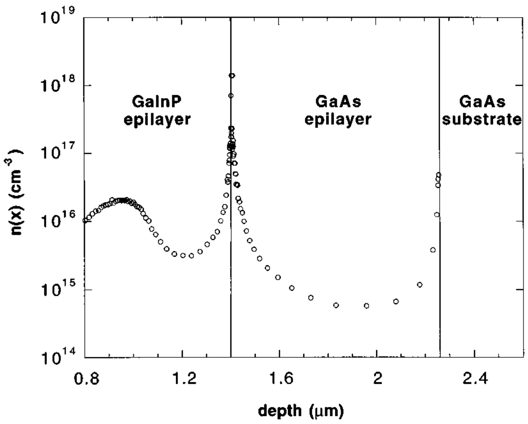

FIG. 5. Capacitance–voltage measured doping profile of GaInP/GaAs material structure.

larger on-resistance than the GaAs devices. This is almost certainly caused by the on-resistance contribution of the conduction band offset and indicates that grading is necessary to reduce the conduction band offset. The reverse $I-V$ characteristics for the GaInP/GaAs sample and the GaAs sample are given in Fig. 4. The GaInP/GaAs sample shows a hard breakdown at ~80 V reverse bias and the GaAs sample shows a relatively soft breakdown at ~20 V reverse bias. This agrees with reported results where MESFET gates on GaAs capped by a thin layer of GaInP have been shown to have an improved breakdown and lower reverse leakage current than MESFET gates on GaAs.[11] The hard breakdown of the GaInP/GaAs sample and the soft breakdown of the GaAs sample may be caused by a difference in the density of surface states and associated surface leakage currents. The maximum parallel plane electric field achieved is about $4–5\times10^5$ V/cm for GaInP/GaAs and about 3.3×10^5 V/cm for GaAs. A plot of doping versus depth for the GaInP/GaAs sample is given in Fig. 5. The plot shows that GaInP/GaAs is a type I heterojunction, with depletion on the GaInP side of the heterojunction and accumulation on the GaAs side of the heterojunction.[12] $C-V$ measurements of the GaAs sample give a doping of $\sim2\times10^{16}$ cm^{-3}.

High quality Schottky rectifiers using a dual-material device structure of GaInP/GaAs exhibit a high breakdown voltage and low reverse leakage current. The dual-material device structure achieves a critcal field ~30% higher and a breakdown voltage approximately 400% higher than a GaAs only device. The conduction band offset of the GaInP/GaAs interface increases the on-resistance well above the mobility limited on-resistance. Therefore, the conduction band offset related on-resistance effects must be reduced by grading or delta doping to achieve the theoretical mobility limited on-resistance of the material structure.

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