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Antimonide-based diodes for terahertz mixers

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Antimonide-based p^+N junctions have been grown by molecular beam epitaxy and processed into diodes. The diodes have good rectification with ideality factors near 1, and high saturation current densities of 2.5×10^{-2} A/cm^2. *S*-parameter measurements to 50 GHz indicate a 1 Ω series resistance and a capacitance of 1.2 fF/μm^2 for a 5 μm diameter mesa diode. A cutoff frequency of 6.5 THz is estimated from the *RC* product. The high saturation current indicates that this diode will reach forward bias currents at substantially lower voltages than GaAs Schottky diodes. These properties suggest using the diode as a terahertz mixer. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2946658]

An antimonide-based heterojunction pn diode has been developed for use as a terahertz frequency mixer diode capable of operating with a low-power local oscillator source. The diode consists of a thin *p*-type narrow-bandgap $In_zGa_{1-z}Sb$ alloy lattice matched to a somewhat larger bandgap *n*-type $In_xAl_{1-x}As_ySb_{1-y}$ alloy as illustrated by the energy band diagram in Fig. 1.[1,2] The diode presented here has a lattice constant of 6.2 Å corresponding to an $In_{0.27}Ga_{0.73}Sb$ semiconductor with a bandgap of 0.5 eV. The low local oscillator power arises from the fact that only 0.5 V is needed to drive the diode into flatband forward bias condition. An additional virtue of this alloy is that it has both high electron and hole mobilities that result in the low series resistance, R_s, needed to minimize the R_sC time constant, where *C* is the diode capacitance, needed for terahertz operation. Increasing the indium content in the InGaSb layer will result in a narrower bandgap *p* layer with a higher saturation current density than reported here further reducing the required local oscillator power. Increasing the indium content will also increase the electron mobility thereby reducing series resistances resulting in higher frequency performance diodes.

Schottky diodes are normally used for high frequency mixer applications as they have a smaller capacitance when forward biased[3–5] than a *pn* diode. The extra capacitance in a *pn* diode is called the diffusion capacitance and it is due to the storage of minority carriers in the quasineutral regions of the diode. The diffusion capacitance is minimized in the p^+N heterojunction diode reported here by using a pair of alloys with a large valence band offset that blocks the holes in the *p* layer from flowing into the *n* layer under forward bias, and by using a thin *p* layer to minimize the storage of minority carrier electrons in the *p* layer. The possibility of minimizing the diffusion capacitance in a *pn* heterojunction has been considered with a different analysis by Sheinman and Ritter.[6]

The layer structure presented in Fig. 2 is for a diode that has been successfully grown on both semi-insultating (SI)-GaAs and SI-InP by solid source molecular beam epitaxy. The growth procedures used were designed to produce random alloys. Not shown in this diagram are the $Al_{0.35}Ga_{0.65}Sb$ and $In_{0.19}Ga_{0.19}Al_{0.38}Sb$ layers that are used to accommodate the lattice mismatch between the substrates and the 6.2 Å lattice constant of the diode layers. Te is used for the *n*-type dopant in the $In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}$, and the *n*-type $In_{0.27}Ga_{0.73}Sb$. Be is used for the *p*-type dopant in the $In_{0.27}Ga_{0.73}Sb$. The ability to produce very low resistance *n*-type $In_{0.27}Ga_{0.73}Sb$ is demonstrated by Hall effect measurements of an electron mobility of 11 000 cm^2/V s with an electron concentration of 9×10^{16} cm^{-3}, and 4500 cm^2/V s at 2.5×10^{18} cm^{-3}. High hole mobilities of 194 and 157 cm^2/V s have been measured for $In_{0.27}Ga_{0.73}Sb$ at hole concentrations of $(1-3)\times10^{19}$ cm^{-3} respectively. Other details of the growth procedures and properties of the alloys have been published, including photoluminescence studies of the band offsets.[7–9] A combination of optical and electron beam lithography techniques was used to produce mesa diodes with diameters from 150 to 5 μm. Additional processing steps were used to fabricate contact pads to facilitate making *S*-parameter measurements.

Current-voltage (*I-V*) measurements and *S*-parameter measurements from 10 MHz to 50 GHz have been made on the diodes. The *S*-parameter measurements were fitted by a model consisting of a parallel combination of a resistor and a capacitor representing the junction in series with a resistor representing the contact and lead resistances. dc *I-V* data for two different layer structures are shown by the solid lines in Fig. 3, along with a dashed curve obtained by fitting

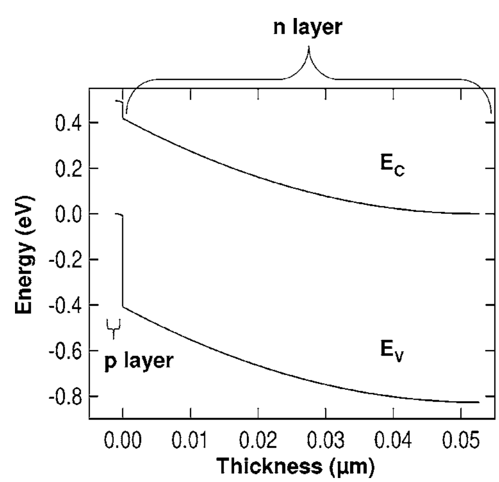

FIG. 1. Energy band diagram to emphasize the very thin *p* layer, the 0.5 eV bandgap of the *p* layer, and the large valence band offset.

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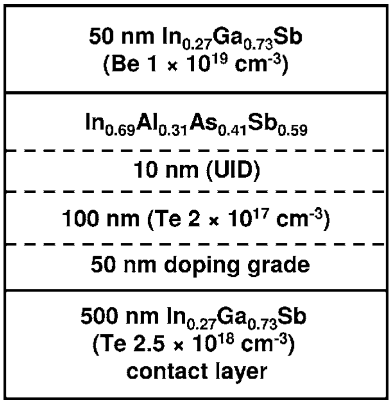

FIG. 2. Layer structure indicating the composition, doping and thickness of a diode. The 10 nm UID layer was included to minimize any possible Te segregation from the heavily doped $In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}$ into the p^+ $In_{0.27}Ga_{0.73}Sb$.

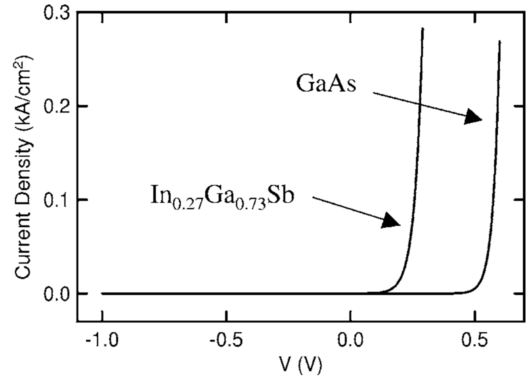

FIG. 4. Comparison of the bias dependence of the dc density for an $In_{0.27}Ga_{0.73}Sb/In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}$ heterojunction *pn* diode and a GaAs Schottky diode. The heterojunction reaches a given current density at a lower dc bias than the GaAs Schottky.

$J=J_{sat}[\exp(qV/\eta k_B T)-1]$ to the forward bias part of the curve. Here J_{sat}, q, V, η, k_B, and T are the saturation current density, electronic charge, applied bias, ideality constant, Boltzmann constant, and temperature, respectively. Curve (a) in Fig. 3 was obtained using the layer structure in Fig. 2, and curve (b) in Fig. 3 was measured for a diode with a 220 nm 5×10^{16} Te doped $In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}$ layer, and without the 10 nm unintentionally doped (UID) layer. $J_{sat}=2.5\times10^{-2}$ A/cm² with $\eta=1.22$ and $J_{sat}=1.1\times10^{-3}$ A/cm² with $\eta=1.05$ were obtained for curves (a) and (b), respectively. The ideality factors are near to one indicating reasonable quality material near the *pn* junction. Good rectification is found over the low voltage range of interest for low-powered devices. *C-V* data extracted from the *S*-parameter data the sample (a) were fitted using a simple one-sided depletion model. The data were indistinguishable from the model over the full reverse bias range to a forward bias of about 0.3 V. At 0.3V the capacitance was slightly above the model fit to the data. This fact will be used later to set an upper limit on the diffusion capacitance. A built-in voltage of 0.51 V and a *n*-type carrier concentration of 1.6×10^{17} cm^{-3} were used to fit the data. These are in good agreement with a built-in voltage of 0.5 V and a carrier concentration of 2×10^{17} cm^{-3} used in the design of the diode. *S*-parameter data for a 5 μm diode from the same wafer as the 20 μm diode were fit to obtain a series resistance of 1 Ω, and zero-bias capacitance of 23 fF corresponding to capacitance of 1.2 fF/μm². 1.2 fF/μm² is similar to the capacitance values reported for GaAs Schottky diodes. A cutoff

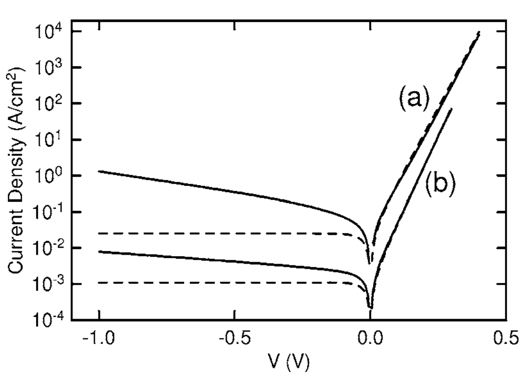

FIG. 3. *I-V* for two different diodes. (a) has the layer structure shown in Fig. 2 and (b) has a lower doped, thicker *n* layer without the 10 nm UID part.

frequency of 6.5 THz is calculated using these values. Considering some of the uncertainties in fitting the *S*-parameter data the cutoff extends between 1.5 and 9 THz.

The low-voltage operation advantage obtained by using this diode compared to the GaAs Schottky barrier diode is illustrated in Fig. 4 where the bias dependence of the current density is illustrated. The curves were calculated using $J=J_{sat}[\exp(qV/\eta k_B T)-1]$ with $J_{sat}=2.5\times10^{-2}$ A/cm², the value obtained for the data shown here for the InGaSb diode, and $J_{sat}=1.6\times10^{-8}$ A/cm² reported in the literature for a GaAs Schottky diode mixer.[5] To be specific in comparing the ability of the InGaSb diode to work at lower power than the GaAs Schottky, the data in Fig. 4 indicate that the InGaSb diode reaches a current density of 100 A/cm² at 0.3 V compared to 0.52 V for the GaAs Schottky.

The diffusion capacitance due to minority carriers in the quasi-neutral region of a *pn* junction, the region between the edge of the depletion region and the neutral bulk part of a diode, can be large and limit the ability of using a pn diode as a high frequency mixer. The large valence band offset shown in Fig. 1 blocks the holes from entering the *n* layer eliminating them as a component of the diffusion capacitance. Estimating the effect of the diffusion capacitance due to minority carrier electrons in the thin *p* layer is more difficult. As mentioned above the *C-V* extracted from *S*-parameter data may be used to set a limit on the diffusion capacitance. At 0.3 V bias the measured capacitance was <44 fF, above the simple depletion model fit to the data. An estimation of the diffusion capacitance, C_{diff}, can be made using $C_{diff}=I\tau/2V_{th}$,[10] where τ is either the electron-hole recombination time in the *p* layer or the time for the electron to diffuse from the *pn* junction to the Ohmic contact to the *p* layer, and $V_{th}=k_B T/q$. Using the dc of $I=1.09$ mA at 0.3 V bias with $V_{th}=26$ meV and $C_{diff}=44$ fF from above results in $\tau=2\times10^{-12}$ s. Using this time, with a dc current of 86 mA measured at a bias of 0.44 V, which is within a few $k_B T$ of the 0.5 V flatband condition, results in an estimate of 3.5 pF for the upper limit of the diffusion capacitance near flatband for this 20 μm diameter diode. This is slightly larger than the 2.5 pF calculated for the depletion capacitance at this bias. This result indicates that using a heterojunction can minimize the diffusion capacitance of a *pn* diode.

Further analysis indicates that τ is the time required for electrons to diffuse across the InGaSb to the Ohmic contact rather than the electron-hole recombination time in the

InGaSb. Therefore as $\tau = w^2/2D$ the diffusion capacitance may be made smaller by reducing the thickness of the InGaSb layer. The fact that minority carrier electrons can transverse a Be doped $In_{0.27}Ga_{0.73}Sb$ like that used here was demonstrated in the development of a heterojunction bipolar transistors (HBT) with a base-emitter junction similar to this pn junction.[11,12] These HBTs are reported to have a current gain of 20. This is a clear demonstration of electron diffusion across the *p* layer without band to band recombination taking place. For consistency $\tau = w^2/2D$ may be used to extract a diffusion constant, $D = 6.25\ cm^2/s$, using $w = 5 \times 10^{-6}$ cm for the thickness of the *p* layer. Using the Einstein relation $D = \mu V_{th}$ results in $\mu = 240\ cm^2/V\ s$ for the mobility of the minority electrons in the $1 \times 10^{19}\ cm^{-3}$ Be doped $In_{0.27}Ga_{0.73}Sb$. Considering the electron mobilities in *n*-type $In_{0.27}Ga_{0.73}Sb$ mentioned above this may be reasonable value for a minority carrier in more heavily doped *p*-type $In_{0.27}Ga_{0.73}Sb$.

In summary, a *pn* heterojunction using a heavily doped *p*-type $In_{0.27}Ga_{0.73}Sb$ layer with a *n*-type $In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}$ layer has been fabricated and its transport properties have been measured. The narrow bandgap *p*-type layer results in the diode having a large saturation current density. This allows it to be used as a mixer diode requiring lower local oscillator power than a GaAs Schottky diode. Further increases in the saturation current can be obtained by increasing the indium fraction in the InGaSb. A small diffusion capacitance at forward bias has been achieved by using a heterostructure with a large valence band offset and a thin InGaSb layer. The diffusion capacitance may be made even smaller by using a thinner InGaSb layer. Other refinements in the device geometry are also possible to reduce the parasitic series resistance that limits the frequency response. *S*-parameter measurements of the diode capacitance and series resistance indicate that terahertz operation is feasible. The need for reduced local oscillator power is important in applications requiring arrays of large number of diodes capable of operating at terahertz frequencies.

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