Schottky Diode Mixers on Gallium Arsenide Antimonide or IndiumGalliumArsenide?

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Abstract— **We have investigated the suitability of using two low-barrier ternary III-V compounds, InGaAs and GaAsSb for Schottky mixers. These materials have lower band-gaps than GaAs, and hence their Schottky barrier heights are lower than those on GaAs. We have found that for Schottky diode mixers employing DC bias, these materials do not yield a reduction in required LO power. However, for mixers that are zero-biased (such as many that are subharmonically pumped), use of these materials in mixers will give a large reduction in required LO power.**

I. Introduction

Schottky mixers remain the heterodyne technology of choice for many submillimeter/ Terahertz applications due to their fair sensitivity and capability for operation at room temperature. For space missions they have one drawback that would be advantageous to overcome: a relatively high local oscillator (LO) pump power requirement. The LO power is required to drive the diode to a high enough current level that it is full switched on.

Diode mixers can be thought of as a switch used to sample the RF signal at the LO frequency. [1, 2]. The diode is a modulated conductance whose peak value should be substantially higher than the RF source conductance presented by the circuit. However, to achieve this the diode must be pumped to an average conductance that is on the order as the RF [2].

The conductance of the diode is determined from it's current using the standard modified thermionic equation. The current at temperature *T* Kelvins is given by:

$$I = AA^{*}T^{2}\exp\left(-q\Phi_{B0}/kT\right)\left[\exp\left(qV/nkT\right)-1\right] \quad (1)$$

with *A* being the diode area, *A** the modified Richardson constant (given by m*/m ×120 A/cm^2/K^2, Φ_{B0} the zero-bias barrier height, and *n* is the ideality factor that models edge and tunneling current effects. Taking the derivative,

$$G \equiv \frac{\partial I}{\partial V} = \frac{q}{nkT} I \quad (2)$$

Hence, the peak conductance is strongly dependent on the barrier height, Φ_{B0}, due to the exponential dependence of I and G. Sub millimeter wave mixers have traditionally been fabricated using metal-on-GaAs contacts with a typical barrier height of around 0.9 to 1.0 eV. Reduction of the barrier height by a few tenths of an eV will give the same values of *G* at diode forward voltage, *V*, several tenths of a volt lower, resulting in an LO power reduction of LO pump power to one fourth or one fifth of that required by GaAs. In this paper we investigate suitable materials to accomplish this.

II. Reduction of LO power details.

Many mixers are unbiased, relying on the rectified LO signal to drive the diode to the needed conductance. These mixers include most submillimeter subharmonically pumped mixers, as well as balanced mixers used at lower frequencies. In this case, the peak LO power can be estimated by first determining the current from the above equation. The LO power can be estimated by converting the peak current to RMS and multiplying by the RMS pump voltage whose peak is close to the diode built-in voltage,

$$V_{b0}\text{: } P_{LO} \approx \frac{1}{2}\frac{nkT}{q} G V_{b0} \quad (3)$$

Using a typical embedding impedance of 100 ohms that circuits in this frequency range can achieve, experience indicates the peak conductance should be around 100 mS (10 ohms). At room temperature using a diode with *n*=1 thus requires a peak LO current of 2.6 mA. If the diode built-in voltage is 0.8, this gives a required diode pump power of about 1 mW per diode. The circuit as a whole will require more, because of losses in the circuit and in the series resistance of the diode.

One way to reduce this requirement is to reduce the pump voltage needed by reducing the barrier voltage, since $qV_{b0} = \Phi_{B0} - qV_n$, with qV_n, being the difference in energy between Fermi level and the bottom of the conduction band in the bulk epi. This is only a few hundredths of an eV in the relatively highly doped diodes used at submillimeter wave freqeuncies, so equation (3) predicts that *reducing the barrier voltage by half will reduce the LO power requirement by half.*

III. Required low-barrier material properties

In order to be useful as a mixer, the material must have several properties, in addition to the low barrier height. To determine their importance, we consider the overall insertion loss. Reference [3] gives a general approximate equation:

$$Loss = \left(1+\frac{R_S}{R_{IF}}\right)\left(1+\frac{R_S}{R_{RF}}+\omega^2 C_j^2 R_S R_{RF}\right) L_{\min} \quad (4)$$

where R_S is the series resistance, R_{RF} and R_{IF} the RF and IF embedding resistances and C_j the average junction capacitance. The quantity $1/C_j^2 R_S R_{RF}$ can be considered the mixer "cutoff frequency", F_{CO}. For properly pumped mixers

C_j is in the neighborhood of 1.5 times the zero-bias capacitance, ie.:

$$C_j \approx 1.5 \times A\sqrt{\frac{q\varepsilon N_D}{2V_{b0}}} \tag{5}$$

L_{min} is the minimum loss that can be determined from the conductance ratio [4]. Under ideal conditions, assuming matched resistances, L_{min} is 3 dB. Note that the assumption has been made that the average junction conductance is matched to R_{RF}. The series resistance is given by:

$$R_S = R_{FIX} + \frac{t_e}{Aq\mu N_D} \tag{6}$$

with R_{FIX} being an area independent resistance associated with the ohmic contact, and μ the mobility. Figure 1 shows the dependence of the cutoff frequency on

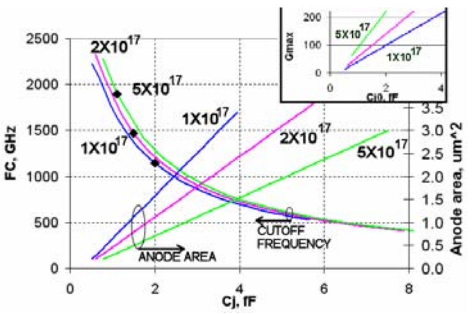


Fig. 1. Diode cutoff frequency and anode size variation with zero-bias capacitance. Inset showss maximum conductance for various diode sizes.

zero-bias junction capacitance, C_{j0} for three different donor concentrations. As can be seen, the F_{CO} is almost unaffected by the doping concentration, although higher dopings are slightly favored. The main limitation on doping is the greater difficulty of lithography needed to fabricate smaller anodes. Figure 1 also indicates the required anode sizes for the three dopings. Clearly, smaller diodes are better, despite the increased series resistance.

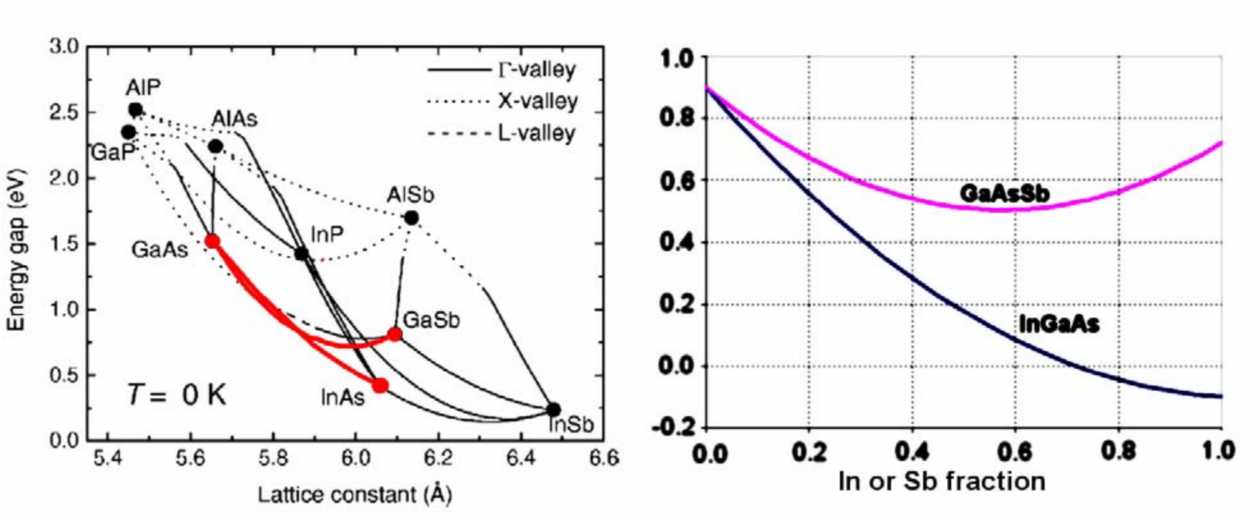
As pointed out in [4, 5] points out, the diode area is limited by current saturation. McColl [4] uses the maximum current density of the thermionic diode model. However, actual velocity saturation due to inter-valley transfer occurs at lower current densities, limiting the maximum velocity to around 1.5×10^7 cm/s. In addition, there is substantial electron heating at that velocity [6], which will add directly to mixer noise. Keeping the heating to a minimum would dictate keeping the peak velocity to around 1×10^7 cm/s. The inset to Figure 1 shows the maximum diode conductance vs C_{j0} for the three dopings. If the target maximum conductivity value is 100 mS, then the minimum C_{j0} values would be around 2, 1.5 and 1.1 fF for dopings of 1×10^{17}, 2×10^{17}, and 5×10^{17} cm^{-3} respectively. These limits are indicated on Figure 1 by the black diamonds.

Clearly the primary qualities needed for the Schottky mixer diode materials are: good mobility and high peak velocity.

IV. Selection of Materials

First, we will find a compound with a Schottky barrier height of about half that of GaAs, around 0.5 eV. Figure 2a shows a band-gap/lattice constant plot of several ternary III-V combinations. The lines connecting the binary endpoints indicate change of band-gap and lattice constant values for various mixtures of the end-point compounds. Considering that the Schottky barrier height is about half to two thirds of the bandgap, are looking for a band-gap of about 0.7 or 0.8 eV. The material GaSb has a gap of 0.7, InAs substantially less. So we will consider the trinary combinations of InGaAs and GaAsSb.

Figure 2b shows the variation of measured Schottky barrier heights of InGaAs and GaAsSb with In or Sb fraction [7, 8]. To yield a barrier height of 0.5 requires InGaAs with an In fraction of 0.25 or so, and GaAsSb with a Sb fraction of about 0.5.



(a) (b)

Fig. 2. (a) Ternary chart of bandgap and lattice constant. (b) Variation of barrier height with In and Sb fraction of InGaAs and GaAsSb.

Let's examine the other properties of these materials. Figure 3 a shows the mobility of GaAsSb and InGaAs doped to 2.3×10^{17} cm^{-3} [9, 10]. As is clear, $In_{0.25}Ga_{0.75}As$

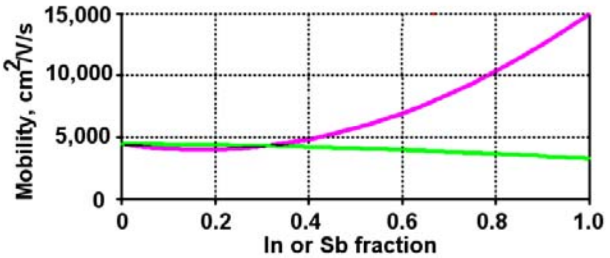


Fig. 3. Variation of material InGaAs and GaAsSb low-field mobility with In and Sb fractions. The donor concentration is 2.3×10^{17} cm^{-3}.

and $GaAs_{0.5}Sb_{0.5}$ have essentially the same mobility as GaAs. Also, since both the mobilities and dielectric constants of the materials are very close to that of GaAs; so Figure 1 is applicable to $In_{0.25}Ga_{0.75}As$ and $GaAs_{0.5}Sb_{0.5}$ for determining the cutoff frequency, according to equations (5) and (6).

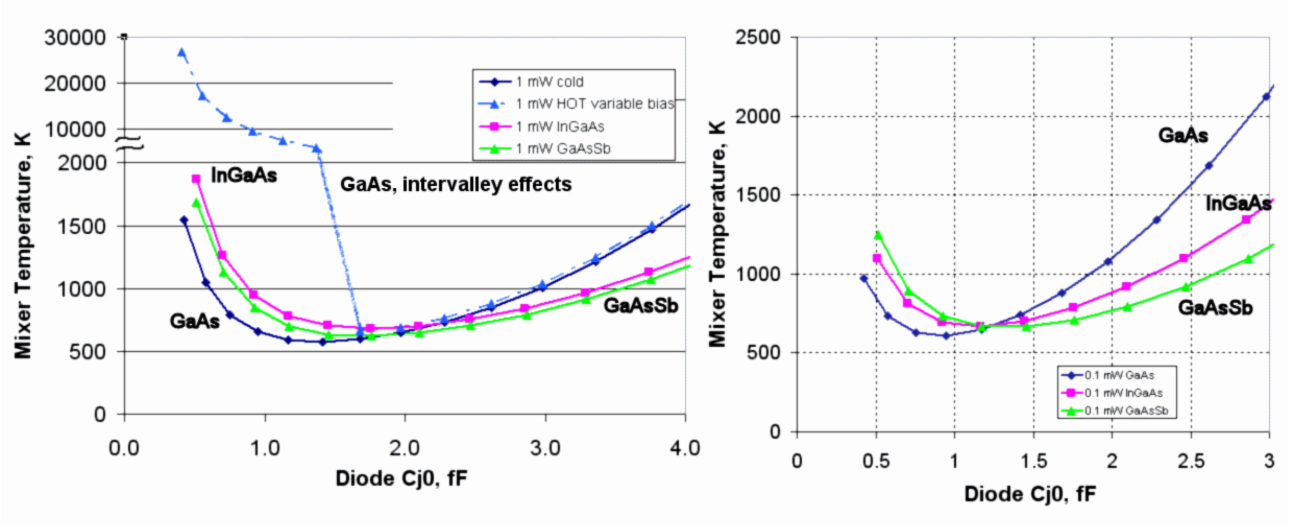
The peak electron velocities of InAs and GaSb are quite different from that of GaAs. The electron velocity of InAs does not reach a peak (i.e. there is no Gunn effect in InAs). Instead it saturates in the range of 7×10^{7} cm/s. The reason is quite simple: velocity saturation is caused by electrons being accelerated to high enough energy to begin phonon assisted scattering out of the central Γ conduction energy-momentum valley into the upper X or L valleys, which have much lower electron mobilities. The L valley is about 0.29 eV above the Γ in GaAs, but for InAs it is a full 0.73 eV higher, thus essentially eliminating transfer to the upper valley.

GaSb is quite different. The L-valley is only 0.1 eV (a few kT/q) above the Γ valley, so electrons readily jump into the L-valley, and electron velocity saturates at around 6×10^{6} cm/s [11], making GaSb a poor candidate for mixer use, not only because of velocity saturation, but because of the inter-valley noise that would accompany the process. Nevertheless, we will ignore this effect in the case of $GaAs_{0.5}Sb_{0.5}$, assuming it is more like GaAs. Nevertheless, before it is seriously considered for mixer diodes, its velocity peak value should be examined.

V. Mixer Analysis

Diodes using these materials were compared using a Harmonic Balance simulator based on [12] using the additions for electron heating as described in [13]. The diode properties were calculated using the information presented above. The conduction current-voltage relation was calculated using the matrix method [14] that incorporates the effect of tunneling current. The embedding resistances were fixed at 100 ohms for LO and RF, and 200 ohms for the IF. The RF reactances were adjusted for optimum performance to compensate for diode capacitance. The doping was set, somewhat arbitrarily at 2×10^{17} cm^{-3}. The LO frequency is 560 GHz.

Figure 4a shows the relevant curves for GaAs, $In_{0.25}Ga_{0.75}As$ and $GaAs_{0.5}Sb_{0.5}$. The mixer is biased, and the LO power level set to 1 mW at the diode. Included for comparison is a calculation based on the authors' work [15] for GaAs. This includes the effect of intervalley transfer in order to model the time-dependent effects of current saturation. This calculation exaggerates the effect because it assumes the entire undepleted epi region has the same fraction of electrons in the upper valley, while Monte Carlo simulations indicate that electron transfer to the upper valley is confined to an area concentrated under the anode. Nevertheless, the diode size where the effect becomes important, around 1.5 fF concurs with Figure 1. Figure 4b includes the same calculation for an LO power level of 0.1 mW. Both calculations indicate that all three materials have similar performance, with the GaAs being consistently, if slightly better. This is due to the fact that



(a) (b)

Fig. 4. Variation of DSB mixer noise temperature with diode size for LO powers of: (a) 1 mW (b) 0.1 mW at the diode level. DC bias is optimized for all cases.

the GaAs ideality factor is better, at least assuming a perfect

interface. Since the barrier heights of $In_{0.25}Ga_{0.75}As$ and $GaAs_{0.5}Sb_{0.5}$ are lower, they have increased tunneling current components, yielding increased ideality factors. A higher ideality factor leads to a lower diode on/off conductance ratio, giving decreased minimum conversion loss and hence a higher mixer temperature.

To explore the effect of LO power on performance using the three materials, a diode with a C_{j0} of 1 fF was analyzed, sweeping the LO power level from 50 μW to 4 mW. Figure 5a indicates the performance with variable bias. As the previous result suggested, the GaAs diode remains the best choice, given variability of DC bias. This is explained by noting that the diode can be biased to the point of optimum conductance ratio, independent of barrier height.

Contrarily, Figure 5b depicts the mixer behavior under varying LO power with fixed zero bias. Zero DC bias is often used for subharmonically pumped and low frequency mixers, for example. Here it is clear that for lower LO powers, the $In_{0.25}Ga_{0.5}As$ or $GaAs_{0.75}Sb_{0.5}$ mixers are superior, and as predicted by equation (3) the LO power required is reduced by about half.

Conclusion

We have analyzed a 560 GHz fundamental mixer using the three material systems GaAs, $In_{0.25}Ga_{0.75}As$ and $GaAs_{0.5}Sb_{0.5}$. The latter two have barrier heights several tenths of a volt below that of GaAs. It is apparent that the higher barrier height and consequent lower tunneling current of GaAs gives it a greater current/voltage nonlinearity and hence lower mixer temperature and conversion loss, even at low LO power, as long as the diode DC bias can be adjusted to put it into the optimum range. If the bias is fixed at zero, however, the $In_{0.25}Ga_{0.75}As$ and $GaAs_{0.5}Sb_{0.5}$ give superior performance at low LO pump power, as predicted by equation (3).

Acknowledgments

The authors gratefully acknowledge helpful discussions with Goutam Chattopadhyay.

The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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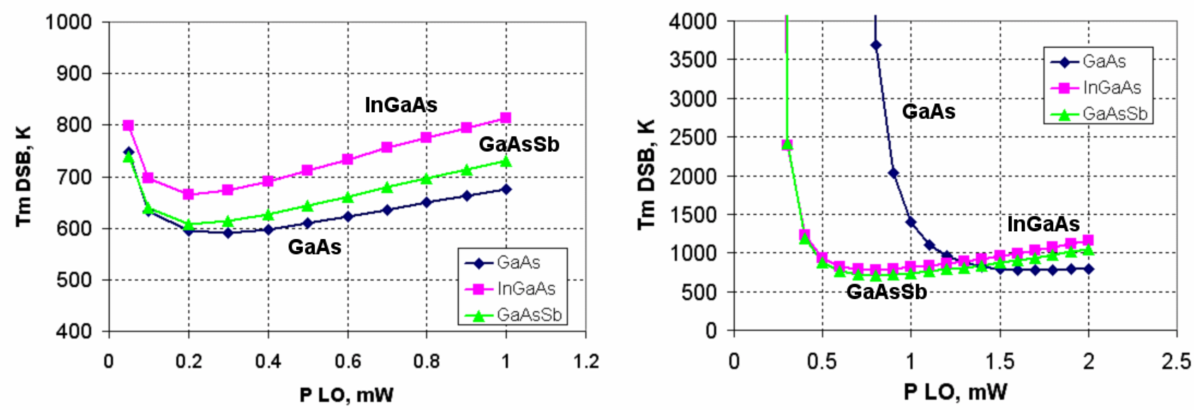

(a) (b)

Fig. 5. Variation of DSB mixer noise temperature with LO pump power. (a) At optimized DC bias values. (b) At zero-bias.