DESIGN, ANALYSIS AND MODELLING OF HETEROSTRUCTURE BARRIER VARACTORS FOR SUB-MILLIMETRE WAVE FREQUENCY QUINTUPLERS

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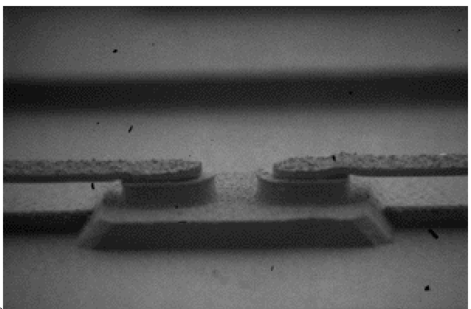
ABSTRACT

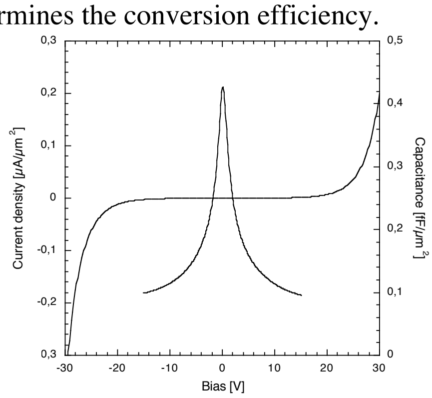
We report on the design, modelling and analysis of heterostructure barrier varactor (HBV) frequency quintuplers with output frequencies in the sub-millimetre wave region. The HBV is a symmetric varactor, thus only odd harmonics are generated and no DC bias is required. By incorporating several barriers in the device, the HBV is also capable of handling higher power levels than conventional varactors. This makes the HBV superior to the conventional Schottky varactor for high order frequency multiplier circuits. We present analytical models, which can be used to calculate parameters such as optimum doping concentration, layer structure, device area and series resistance for HBVs, as well as to predict the performance with respect to conversion efficiencies and output power levels. These parameters are then further optimised by harmonic balance simulations in commercial microwave EDA tools, for which we have developed accurate device models. We investigate the influence of embedding impedance levels for optimum conversion efficiency by means of analytical expressions and harmonic balance simulations. Theoretical calculations predict a maximum diode conversion efficiency to 500 GHz for a planar, six-barrier InGaAs HBV of more than 30 %.

INTRODUCTION

The heterostructure barrier varactor (HBV) [1] is a symmetric varactor consisting of a high band gap semiconductor (barrier), surrounded by moderately doped modulation layers of a semiconductor with a lower band gap. The barrier prevents electron transport through the structure. When an external signal is applied to the HBV, electrons are accumulated at on side and depleted at the other side of the barrier, causing a symmetric, voltage dependent capacitance. Figure 1(a) shows a SEM picture of a planar HBV fabricated at Chalmers, where two mesas are connected in series. The symmetric C-V and anti-symmetric I-V characteristics of a typical HBV is shown in Figure 1 (b). The main advantage with HBVs is the possibility to tailor the layer structure of the device for various applications. The power handling capability can be increased by stacking several barriers epitaxially, or by series connecting mesas. The thickness and doping concentration of the modulation layers have a great influence on the dynamic cut-off frequency, which determines the conversion efficiency.



(a)



(b)

Figure 1. *(a) SEM picture of a planar HBV fabricated at Chalmers.*
(a) C-V and J-V characteristics of a typical HBV (CTH-ITME-1819).

OPTIMISATION OF THE MATERIAL LAYER STRUCTURE

Choice of material system

HBVs are exclusively fabricated from III-V heterostructures, principally GaAs/AlGaAs on GaAs and InGaAs/InAlAs on InP. GaAs based HBVs exhibit high breakdown voltages but suffer from excessive leakage, which lowers the conversion efficiency significantly [2]. State-of-the-art HBVs are fabricated using $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ on InP [3]. This system offers higher electron velocities and the electron potential barrier is higher compared to GaAs based systems, which means lower leakage currents and, thus, higher conversion efficiencies of frequency multipliers. The simulations in the following sections assume an InP based material system.

Conversion efficiency

The conversion efficiency of an HBV is closely related to the dynamic cut-off frequency, which therefore needs to be maximised. The dynamic cut-off frequency is defined as

$$f_c = \frac{S_{\max} - S_{\min}}{2\pi R_s} \tag{1}$$

where $S_{\max}$ and $S_{\min}$ are the maximum and minimum elastances, respectively, and R_S is the series resistance. The diode conversion efficiency for quintupler operation can be approximated as

$$\eta \approx \frac{100}{1 + 200 \cdot \left(\frac{5}{3} \cdot \frac{f_p}{f_c} \right)^{1.5}} \% \tag{2}$$

where f_p is the pump frequency [4]. The temperature dependent series resistance of a planar HBV, with the geometry shown in Figure 1 (a), can be estimated as

$$R_s(T) = R_{active} + 2R_c + 2R_{cl} + R_{spread,buffer} \tag{3}$$

where R_{active} is the resistance of the modulation layers, R_c is the ohmic contact resistance, R_{cl} is the resistance of the highly doped contact layers, and $R_{spread,buffer}$ is the spreading resistance of the buffer layer between the two series connected mesas. All terms of (3), except the ohmic contact resistance, are calculated from the low field mobility of InGaAs. We use the model for low field mobility as a function of doping concentration and temperature reported in [5].

Optimum doping concentration

Figure 2 shows the cut-off frequency, calculated from (1), versus doping concentration in the modulation layer for an InP HBV structure with 2 to 8 barriers. In order to achieve feasible impedance levels, the area in these calculations is chosen so that

$$\frac{1}{2\pi f_p C_{\max}} = 100, \tag{4}$$

where C_{max} is the maximum capacitance of the device. From Figure 2 it can be seen that the optimum doping concentration in the modulation layers is around 10^{23} m^{-3}. However, it should be emphasised that no effect due to self-heating has been considered in the calculations for Figure 2. If too many barriers are stacked epitaxially the device temperature will be very high, which degrades the cut-off frequency [6]. Also, the area for each data point in Figure 2 is chosen according to (4), which means that the area is not constant.

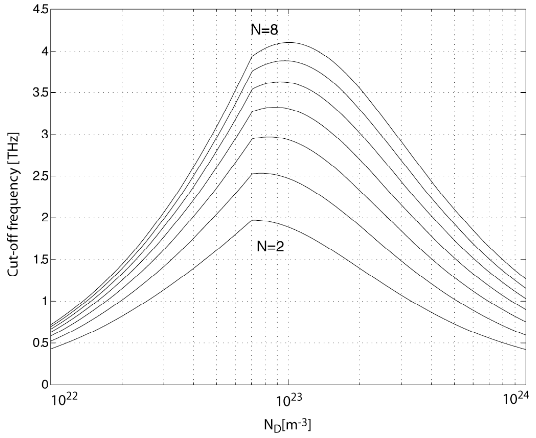


Figure 2. Cut-off frequency versus modulation layer doping concentration for an InP based HBV material with N=2 to N=8 barriers.

OPTIMUM EMBEDDING IMPEDANCES

This section investigates optimum embedding impedance levels for 500 GHz HBV quintuplers. First, analytical expressions are used to estimate optimum impedances for a given HBV structure, see e.g. [7]. These impedances are then optimised in Microwave Office, using an in-house HBV model, to predict the performance in terms of conversion efficiency and corresponding power levels.

Harmonic balance simulations

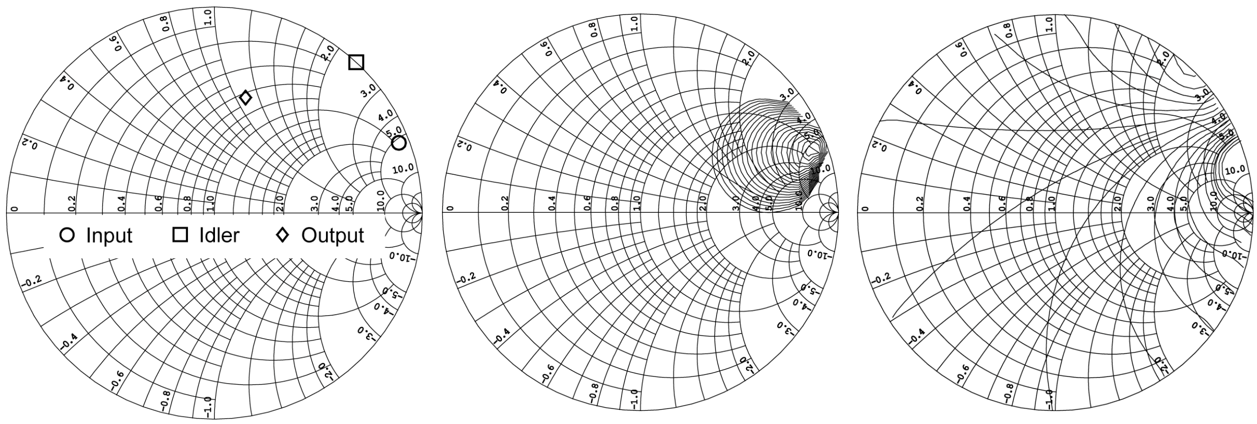
Harmonic balance simulations have been carried out using Microwave Office, for which we have developed an accurate HBV diode model. The model is based on the following expression for the voltage across the device versus the charge stored in the HBV [8]:

$$V(Q) = N\left(\frac{bQ}{\varepsilon_b A} + 2\frac{sQ}{\varepsilon_d A} + Sign(Q)\left[\frac{Q^2}{2qN_D\varepsilon_d A^2} + \frac{4kT}{q}\left(1 - e^{-\frac{|Q|}{2L_D A q N_D}}\right)\right]\right) \quad (5)$$

The available input power level around 100 GHz is typically 100 mW, i.e. 20 dBm. We assume that the input losses can be limited to 1 dB, and thus the pump power at 100 GHz is set to 19 dBm in the simulations. In order to exemplify, we use a fictitious material, OPT, optimised for 500 GHz quintupler applications. The material is $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ on InP. The OPT material is assumed to have 2×3 barriers, a doping concentration in the modulation layer of $9.2 \cdot 10^{22}$ m^{-3} and a thickness of the modulation layers of 250 nm. This gives a series resistance of 10.4 Ω and a dynamic cut-off frequency of 4.3 THz.

Simulation results

The harmonic balance simulations predict a diode conversion efficiency to 500 GHz of approximately 31%, corresponding to minimum conversion loss of 5.1 dB, for the OPT HBVs. The device area is chosen to 37 μm^2, in order to assure that the modulation layers are fully depleted when pumped with 19 dBm of input power at 100 GHz. Figure 3 shows the embedding impedances for maximum conversion efficiency and contour plots of the conversion loss versus input and idler (third harmonic) reflection coefficients for OPT HBVs. Each contour corresponds to an increase in conversion loss of 1 dB. It is clear that the input matching is very crucial, whilst a non-optimum idler reflection coefficient will not have a very large impact on the circuit performance, as long as the reactance is kept smaller than the optimum value. An accurate impedance match at the input can be achieved by using moveable tuners.



(a) (b) (c)

Figure 3. (a) *Optimum embedding impedances for OPT HBVs for a 500 GHz quintupler.*
(b) *Conversion loss contours versus input reflection coefficient.*
(c) *Conversion loss contours versus idler (third harmonic) reflection coefficient.*

Conclusions

We have presented methods for the design and analysis of HBV frequency quintuplers. HBVs were optimised using new analytical, temperature dependent models. Optimum embedding impedances and estimated circuit performance were obtained from harmonic balance simulations in Microwave Office, for which HBV models have been developed.

Acknowledgements

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References

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