HETEROSTRUCTURE BARRIER VARACTOR MULTIPLIERS

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ABSTRACT

The Heterostructure Barrier Varactor (HBV) diode and its application in frequency multipliers is reviewed. Different material systems and HBV models are described. Multiplier performance versus diode parameters and some practical multiplier designs are discussed as well. The best result until now is an efficiency of 12% and an output power of 9 mW at an output frequency of 250 GHz.

INTRODUCTION

The Heterostructure Barrier Varactor (HBV) diode was introduced about ten years ago, Kollberg and Rydberg (1), (2), and has received considerable attention as a promising symmetric varactor element for frequency multiplier applications at millimetre and submillimetre wave frequencies. Since this varactor has a capacitance-voltage, C(V), characteristic which has even symmetry around V=0, it will only produce odd harmonics, $(2n+1)\omega_p$, when pumped with power at the fundamental frequency, ω_p. The absence of even harmonics simplifies the realisation of higher order multiplier circuits. For the tripler case, it is possible to build a multiplier circuit by considering the pump frequency and the output frequency only. As a result of the simplified circuit, design of frequency multipliers operating over a wider frequency range is possible. The HBV has the advantage of allowing epitaxial stacking, which increases its power handling capacity considerably, Krishnamurthi et al. (3) and Rahal et al. (4).

The device uses a high bandgap semiconductor sandwiched between low bandgap semiconductors (Figure 1). The high bandgap material (barrier) prevents electron transport through the structure. When the structure is biased, electrons are accumulated on one side of the barriers and depleted on the other side of the barriers. The resulting C(V) is shown in Fig. 2.

HBV MATERIAL SYSTEMS

It is necessary that the barrier material and the modulation layer material have almost the same lattice constants to avoid lattice dislocations and inferior performance. It is indeed possible to grow dislocation free layers with a small lattice mismatch if the layers are thinner than a critical thickness. Historically, the first HBV diode was realised using $GaAs/Al_{0.7}Ga_{0.3}As$ grown on a GaAs substrate, Rydberg et al (2). GaAs/AlGaAs is well characterised and relatively simple to process. A drawback with this device is the comparatively large conduction current due to a low conduction band offset and corresponding low barrier hight. The conduction current causes a deteriorated efficiency. It has also been shown that the temperature increases when the diode is pumped, which further increases the conduction current and leads to an even lower efficiency, Stake et al. (5).

A more efficient material system is $In_{0.53}Ga_{0.47}As/Al_{0.48}In_{0.52}As$ grown on an InP substrate. This material system offers a large conduction band offset, especially if a layer of AlAs is inserted in the middle of the barrier. However, it is very difficult to grow thick epilayers on InP by MBE. Rather thick epilayers are needed for planar HBVs, since they use thick buried contact layers, and for HBVs with a large number of barriers. However, it has recently been shown that very good HBV material can be grown by MOVPE, Strupinski et al. (7). A successful material grown by MOVPE is presented in Table 1 (Strupinski et al. (7)). The structure, originally designed for planar devices, is similar to HBV materials grown by MBE, but with larger undoped spacer layers to prevent diffusion of silicon into the barrier layers.

A lower doping concentration in the modulation layers results in a higher break down voltage with low conduction current and a low minimum capacitance. Typically a current density • 0.1 $\mu A/\mu m^2$ is required for good efficiency, yielding a maximum voltage of 6V per barrier for $N_d=7\cdot 10^{16}$ cm^{-3} in the modulation layers. A drawback with a low doping concentration is that it results in a high resistivity which increases the losses and decreases the cut-off frequency. MOVPE material is now equal in performance to MBE material, Strupinski et al. (7), Lheurette et al. (8). For more extensive information about the design of HBVs, see Stake et al. (9).

MULTIPLIER EFFICIENCY

The dynamic cut-off frequency (Eq. 1) has the strongest influence on the efficiency of the multiplier. The dynamic cut-off frequency f_c is calculated as

$$f_c = \frac{1}{2\pi R_s}\left(\frac{1}{C_{min}} - \frac{1}{C_{max}}\right) \qquad (1)$$

where R_s is the series resistance and C_{min} and C_{max} are the minimum and maximum capacitance during one pump cycle.

A systematic investigation was presented by Dillner et al. (10). Typically the ratio C_{max}/C_{min} should be three or higher. A ratio of six only increases the cut-off frequency with 25%.

For a quintupler, the idler impedance is important. If no current is allowed at the idler frequency (i.e. Z_3=•), the third harmonic current of course will not cause any extra losses at all. However, it is very interesting that the multiplier efficiency anyhow is low, a fact which is due to the symmetric properties of the C(V). On the other hand, if one maximises the current at the idler frequency with an inductance in resonance with the diode capacitance at the idler frequency, a maximum efficiency is obtained, Dillner et al. (10).

It is interesting to compare quintuplers with triplers as power sources for the same output frequency. A varactor diode is usually dimensioned from the output impedance. Since the output impedances are approximately equal for triplers and quintuplers, triplers and quintuplers with the same diode capacitance can be compared. Referring to Figure 3 it is shown that the maximum efficiencies are almost equal, except for output frequencies near the cut-off frequency. This indicates that quintuplers have an advantage over the triplers, since since they use a lower input frequency where more powerful sources are available. The circuit is more complicated for quintuplers since the impedance at the idler frequency has to be optimised.

As already mentioned the conduction current is a limiting factor for the efficiency. The small signal conductance is, as the capacitance, voltage dependent. If the ratio $G_{max}/(C_{min}\omega_p)<0.1$, the conductance current will not deteriorate the efficiency more than a few tenths of a dB.

FREQUENCY MULTIPLIER EXPERIMENTS

The first HBV diode was tested in a crossed-waveguide frequency tripler. The single barrier GaAs/AlGaAs HBV was contacted with a whisker wire, Rydberg et al. (2). A maximum output power of 1 mW was generated at 225 GHz and the peak flange-to-flange efficiency was 3.1 %.

A planar four barrier GaAs/AlGaAs HBV diode (two series coupled two-barrier diodes) was tested in a crossed-waveguide frequency tripler, Jones et al. (11). A maximum output power of 2 mW was generated at 252 GHz and the peak efficiency was 2.5 %. For a planar four barrier (two series coupled two-barrier diodes) GaAs/AlGaAs HBV diode with an improved diode geometry (Figure 4), 4 mW output power and 4.8 % efficiency was obtained at an output frequency of 246 GHz, Stake et al. (12).

A planar four barrier (again two series coupled two-barrier diodes) InGaAs/InAlAs HBV diode was tested in a crossed-waveguide frequency tripler, Mélique et al. (13). A maximum output power of 9 mW was generated at 250 GHz and the peak efficiency was 12 %. This is the best HBV multiplier performance obtained so far.

In a new design the InP substrate is etched away and replaced with pure copper, Dillner et al. (14). This offers not only lower series resistance but also an improved thermal heat sink, which improves the power handling capacity. In a recent tripler experiment using a crossed waveguide mount, Dillner at al. (6) (see Fig. 5), and this new diode, a maximum output power of 7.1 mW was generated at 221 GHz with a flange-to-flange efficiency of 7.9 %.

In addition to the crossed waveguide multiplier, two other HBV multiplier topologies, Hollung et al. (15-16), have been developed. One is a broadband distributed HBV frequency tripler consisting of a finline transmission line periodically loaded with 15 HBV diodes, see Fig. 6. This frequency tripler uses planar diodes with two barriers and exhibits 10 mW peak radiated power at 130 GHz with more than 10% 3-dB bandwidth and 7% conversion efficiency.

The second design is a quasi-optical HBV diode frequency tripler consisting of two slot antennas loaded with four planar HBV diodes and located at the focal plane of a dielectric lens, Fig. 7. The quasi-optical tripler demonstrates a radiated power of 11.5 mW and a conversion efficiency of about 8 %.

Single barrier InGaAs/InAlAs HBV diodes have also tested in a crossed-waveguide frequency quintupler, Räisänen et al. (17). 0.78 % efficiency was reported at an output frequency of 172 GHz.

CONCLUSION

The heterostructure barrier varactor has in multiplier experiments shown to be capable of efficient power generation in the shorter millimetre wave range. The efficiency of planar GaAs/AlGaAs HBV multipliers is severely reduced due to self-heating of the diode. This problem can be solved by modifying the epitaxial structure, and improving the heat-sink. High quality HBV material can be grown by MOVPE. HBVmultipliers with high efficiency and wide bandwidth have been demonstrated. We predict that HBV quintuplers can be very competitive as high frequency power sources.

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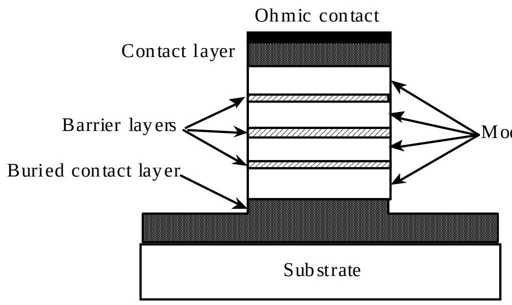

Figure 1. Epitaxial layer structure of a three barrier HBV.

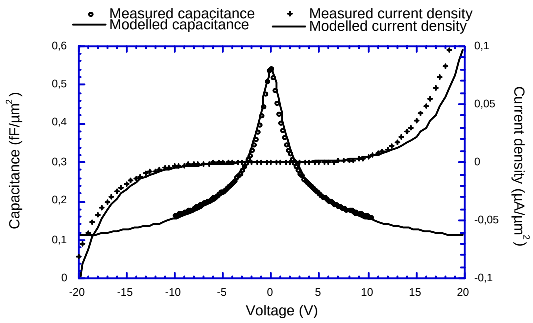

Figure 2. Capacitance-voltage characteristics and current density for a three-barrier HBV (ITME 1622).

Table I: ITME 1622 HBV Material structure

	Material	Doping	Thickness
Contact	InAs	n^{++}	10 nm
Contact	$In_{.53-1}Ga_{.47-0}As$	n^{++}	600 nm
Modulation	$In_{.53}Ga_{.47}As$	$7 \cdot 10^{16} cm^{-3}$	400 nm
Barrier and spacer		i	
Modulation	$In_{.53}Ga_{.47}As$	$7 \cdot 10^{16} cm^{-3}$	400 nm
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Modulation	$In_{.53}Ga_{.47}As$	$7 \cdot 10^{16} cm^{-3}$	400 nm
Barrier and spacer		i	
Modulation	$In_{.53}Ga_{.47}As$	$7 \cdot 10^{16} cm^{-3}$	400 nm
Buried contact	$In_{.53}Ga_{.47}As$	n^{++}	2000 nm
Substrate	InP	S.I.	

Barrier & spacer layers: $In_{.53}Ga_{.47}As$: 40 nm, $In_{.52}Al_{.48}As$, 5 nm . 3 nm AlAs, 5 nm $In_{.52}Al_{.48}As$, 40 nm $In_{.53}Ga_{.47}As$

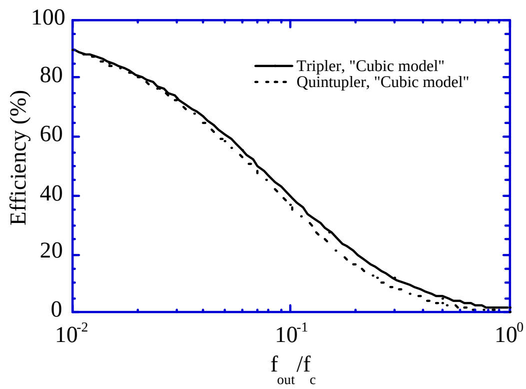

Figure 3. Maximum tripler and quintupler conversion efficiencies for the same output frequency.

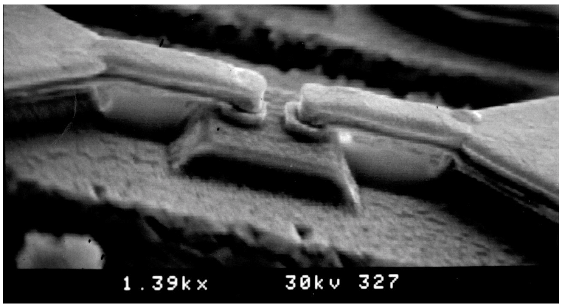

Figure 4. Planar HBV design incorporating a short finger with a cross section to reduce thermal resistance of the diode (13).

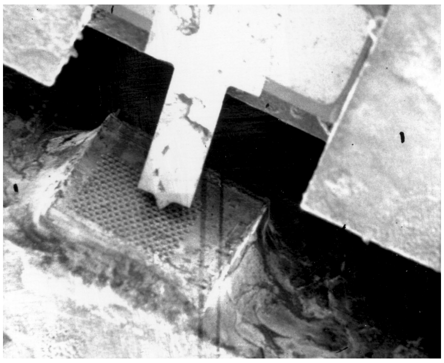

Figure 5. A chip mounted in the output waveguide large with HBVs contacted using a planar whisker.

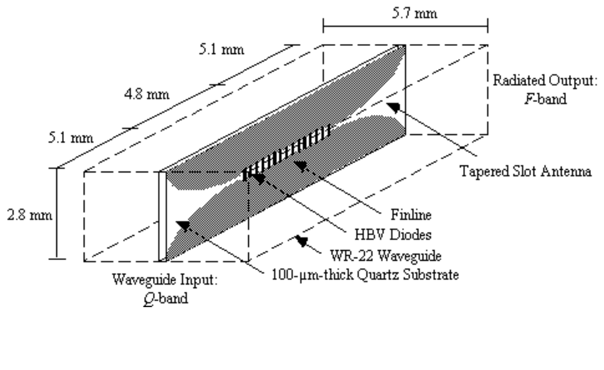

Figure 6. Non-linear transmission line tripler consisting of two tapered slot antennas and a finline loaded with 15 HBVs on a 100 µm-thick quartz substrate.

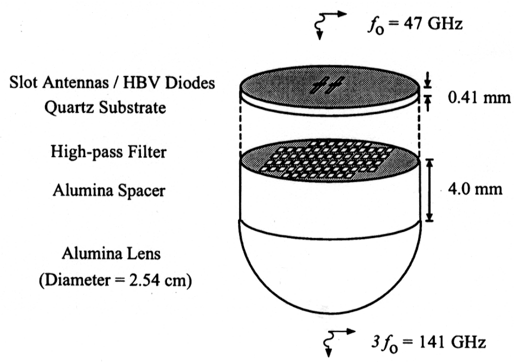

Figure 7. Quasi-optical tripler, consisting of two slot antennas loaded with four HBV diodes and located at the focal plane of a dielectric lens.