Heterostructure Barrier Varactor Frequency Triplers to 220 – 325 GHz

Yiwei Duan, Qun Xiao, Jeffrey L. Hesler, and Thomas W. Crowe
Department of Electrical and Computer Engineering
University of Virginia, Charlottesville, VA 22903 USA

Abstract --- HBV frequency triplers to the WR-3 waveguide band have been designed, fabricated and tested. The epitaxial materials used were from the InGaAs/InAlAs material system. The initial batch of discrete planar HBVs was designed and fabricated based on a three-barrier epitaxial wafer. Individual chips were fabricated and flip-chip mounted on existing quartz circuits designed for a Schottky diode tripler. Test results showed that these six-barrier planar HBVs could not be fully pumped with available input power of about 100mW. To achieve better performance in terms of efficiency and output power, a two-barrier epitaxial wafer with lower doping in the modulation layers was designed and purchased. With the same mask set as for the previous run a batch of discrete planar HBV was fabricated with this new wafer and tested.

Next, integration of the HBV diodes directly on the quartz circuit was considered and determined to reduce parasitic capacitance, ease assembly and improve reliability. Therefore our semiconductor-on-quartz integration process was modified to allow the formation of InGaAs mesas and an integrated version of the HBV circuit was designed and fabricated. This batch of integrated HBV triplers showed dramatically improved performance. Output power of 3.87 mW and efficiency of 4.5% at 300 GHz were measured with an Erickson PM1B power meter (about 6mW was measured with an Anritsu WR-3 meter). Issues concerning the epitaxial wafer design, device fabrication and tripler testing will be presented in this paper.

I. INTRODUCTION

People are becoming more and more interested in millimeter and submillimeter-wave technology for such applications as radio astronomy, chemical spectroscopy and atmospheric studies [1, 2, 3]. However, this frequency range is technologically very challenging, and amplifiers are not available. Therefore, heterodyne receivers are used in this research field to convert, by frequency mixing, the high frequency spectrum to a low frequency range where it can be amplified and analyzed. In this application, millimeter and submillimeter-wave local oscillators with sufficient output power are needed. Because fundamental oscillators and amplifiers do not work well above about 150 GHz, frequency multipliers, i.e. nonlinear harmonic generators, are widely used. In principle, any nonlinear impedance can be used to generate frequency harmonics. However, variable capacitance, or varactor, diodes have better efficiency and power handling capabilities than variable resistance, or varistor, diodes for this application.

HBV's, which were proposed by Kollberg in 1989 [4], have excellent characteristics for frequency tripling. Primarily, this is because HBV diodes have a symmetric C-V characteristic. Thus, for triplers using HBV's, the second harmonic idler circuitry is not necessary because only odd harmonics are produced. Furthermore, DC bias is not needed because the capacitance modulation region is centered at zero-bias. Therefore, the circuit design is much simpler than that required for a standard Schottky varactor. Also, due to the stackable barrier structure of HBVs, large power handling ability can be achieved by stacking more barrier layers vertically instead of putting more diodes in series as is done with Schottky diode frequency multipliers. HBV triplers have recently been demonstrated to have good performance to WR-3 band frequencies by this research and others [5, 6].

II. DEVICE FABRICATION

To make an HBV frequency tripler with greater efficiency, lower leakage current through the barrier is preferred. Therefore materials with higher barrier height are preferred. So InGaAs/InAlAs/InGaAs materials were chosen in our research instead of GaAs/AlGaAs/GaAs.

The MBE grown 3-inch diameter epitaxial wafers were purchased from Global Communication Semiconductors, Inc. <http://www.gcsincorp.com/>. The first structure is shown in Table 1. Strained thin layers of AlAs are added to improve the barrier height [7]. The InAs capping layer was added to make non-alloyed ohmic contacts [8].

	Layer Thickness	Layer Doping	Material	Repeat
n^{++} Contact Layer	10nm	n^{++}	InAs	
	40nm	n^{++}	$In_xGa_{1-x}As$ x=0.53 to 1	
	100nm	n^{++}	$In_{0.53}Ga_{0.47}As$	
Modulation	300nm	$1.7X10^{17}cm^{-3}$	$In_{0.53}Ga_{0.47}As$	
Spacer	20nm	u-d	$In_{0.53}Ga_{0.47}As$	
Barrier	5nm	u-d	$In_{0.52}Al_{0.48}As$	
	3nm	u-d	AlAs	X 3
	5nm	u-d	$In_{0.52}Al_{0.48}As$	
Spacer	20nm	u-d	$In_{0.53}Ga_{0.47}As$	
Modulation	300nm	$1.7X10^{17}cm^{-3}$	$In_{0.53}Ga_{0.47}As$	
n^{++} Buffer Layer	3μm	n^{++}	$In_{0.53}Ga_{0.47}As$	
Substrate	650μm	SI	InP	

Table 1: Lattice matched InGaAs/InAlAs/InGaAs on InP substrate for 6-barrier HBV.

To evaluate the quality of the epitaxial material, whisker contacted HBV's with large mesas (diameter of 70um) were made on a 0.2 by 0.2 inch square wafer and tested. Then discrete planar HBV's were made on a 0.4 by 0.5 inch wafer. The fabrication processing includes the following steps, 1. modulation mesa etch, 2. ohmic contact metals evaporation and lift-off, 3. ohmic contact thermal treatment (around 330 C° to 340 C°), 4. planarization and ohmic contact area reopening, 5. seed layer gold sputtering, 6. finger and contact pad patterning and gold plating, 7. photoresist and seed layer gold removal, 8. surface channel isolation etch, 9. substrate thinning and device separation. Several variations of HBV's with different mesa sizes were fabricated. An SEM picture of a discrete planar HBV before separation is shown in Fig. 1.

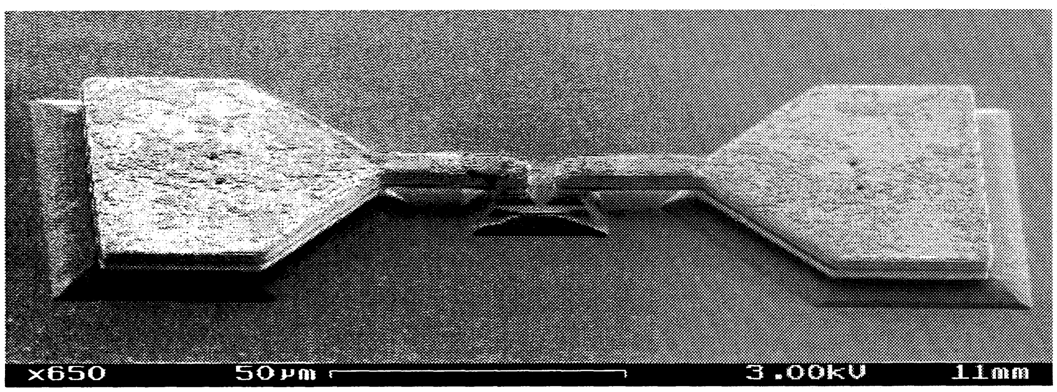

Fig. 1: SEM of a discrete planar HBV before separation.

Flip-chip mounting of the discrete HBV diode onto a quartz circuit is always a hard task to fulfill. Integration of the HBV diodes with the quartz circuit during the device fabrication process makes the tripler block assembly much easier. It also provides perfect alignment of the diode to the circuit and reduces shunt capacitance. Therefore, integration should improve tripler performance, repeatability and reliability.

The integrated HBV circuits were made on a 0.4 by 0.5 inch wafer. The fabrication processing includes the following steps, 1. wafer bonding on quartz, 2. modulation mesa etch. 3. non-alloy ohmic contact metals evaporation (Ti 1000Å / Au 2000Å) and lift-off, 4. n^{--} mesa etch, 5. planarization and ohmic contact area reopening, 6. seed layer Ti and Au evaporation and Au sputtering, 7. finger and circuit patterning and gold plating, 8. photoresist and seed layer metals removing, 9. substrate thinning and device separation. An SEM image of an integrated HBV circuit before separation is shown in Fig. 2.

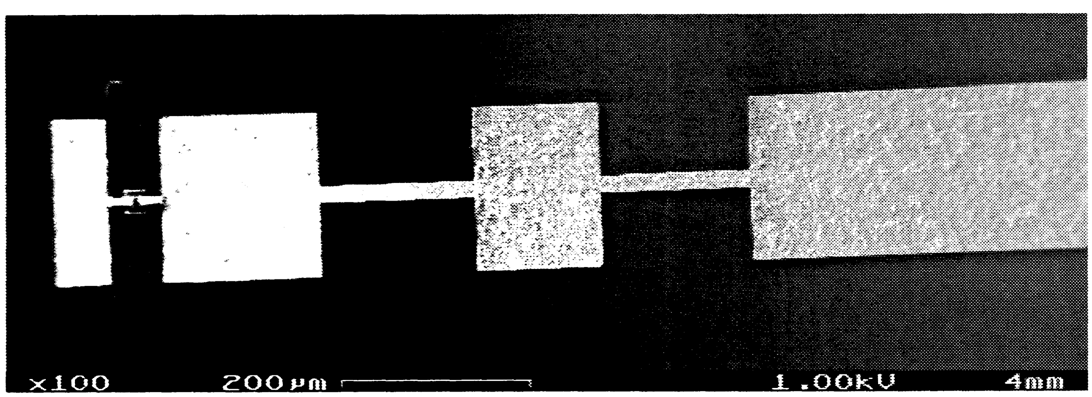

Fig. 2: An SEM view of an integrated HBV circuit before separation. The dark areas are the quartz substrate, the light areas are the deposited metal circuitry and the small InGaAs mesa is shown near the left end and is contacted by two air-bridged fingers.

III. DC AND RF MEASUREMENTS

A. Whisker Contacted HBV

The C-V and I-V characteristic of the 6-barrier whisker contact HBV were measured, and they showed good symmetry and anti-symmetry, respectively. However, the measured value of capacitance at zero bias (1.6pF, see Fig. 3) is significantly larger than calculated (1.1pF). The calculation is based on [9], in which the spacer layers are modeled as part of the barrier when calculating junction capacitance. If the effect of the spacer layers is excluded, the calculated capacitance at zero bias is 2.2pF. Therefore, we believe that a significant number of electrons from the modulation layers have diffused into the spacer layers and thereby increased the zero bias junction capacitance.

B. Six-Barrier-Discrete-HBV Frequency Triplers

After testing at DC bias, a discrete 6-barrier HBV was flip-chip mounted onto a quartz circuit and assembled into a tripler block. The RF testing result is shown in Fig. 4. This data indicates that the efficiency has not saturated at the maximum available input power. Thus, the 6-barrier HBV frequency tripler could have even higher efficiency with higher input power. In other words, these HBV diodes are not optimized at the maximum available input power. Therefore, we decided to fabricate another batch of HBVs with only four barriers to reduce the amount of power required for optimum efficiency.

C. *Four-Barrier-Discrete-HBV Frequency Triplers*

The epitaxial structure for 4-barrier HBVs is shown in Table 2. Compared to the 6-barrier design, this wafer has fewer barriers (reduced from 3 to 2), lower modulation layer doping (reduced from $1.7 \times 10^{17}cm^{-3}$ to $1.0 \times 10^{17}cm^{-3}$) and thinner spacer layers (reduced from 20nm to 5nm). The first two modifications were made to increase efficiency at the available input power. The spacer layers are used to prevent dopant diffusion and electron wave function penetration [7]. However, we concluded that five nanometers thick spacer layers are sufficient. The thinner spacer layers also make the C_{max}/C_{min} ration larger, thereby yielding higher cut-off frequency and better efficiency [9, 10].

The RF testing result of one tripler is shown in Fig. 5. Because the mask set for previous 6-barrier HBV was used to fabricate this batch of 4-barrier HBV diodes, the junction capacitance of this batch is 50% larger. Therefore, the cutoff frequency is lower and testing was performed at 81/243 GHz.

Several sample diodes were sent to Dr. Chris Mann at the Rutherford Appleton Laboratory (UK). Their tripler block has both input and output tuning back shorts to optimize coupling, while our block has only an input E-H tuner attached externally to the block. The RAL results, shown in Fig. 6, are excellent and demonstrate the quality of this batch of HBV diodes.

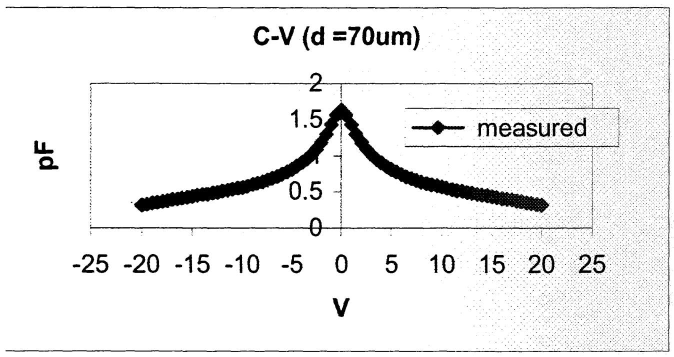

Fig. 3: C-V curve of a six-barrier whisker contacted HBV.

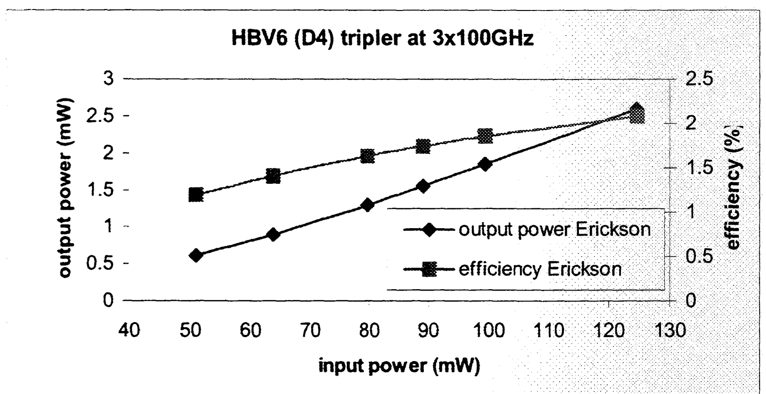

Fig. 4: Output power and efficiency of a 100/300GHz frequency tripler with a 6-barrier discrete HBV.

	Layer Thickness	Layer Doping	Material	Repeat
n^{++} Contact Layer	10nm	n^{++}	InAs	
	40nm	n^{++}	$In_xGa_{1-x}As$ x=0.53 to 1	
	100nm	n^{++}	$In_{0.53}Ga_{0.47}As$	
Modulation	300nm	$1.0X10^{17}cm^{-3}$	$In_{0.53}Ga_{0.47}As$	
Spacer	5nm	u-d	$In_{0.53}Ga_{0.47}As$	X 2
Barrier	5nm	u-d	$In_{0.52}Al_{0.48}As$	
	3nm	u-d	AlAs	
	5nm	u-d	$In_{0.52}Al_{0.48}As$	
Spacer	5nm	u-d	$In_{0.53}Ga_{0.47}As$	
Modulation	300nm	$1.0X10^{17}cm^{-3}$	$In_{0.53}Ga_{0.47}As$	
n^{++} Buffer Layer	3μm	n^{++}	$In_{0.53}Ga_{0.47}As$	
Substrate	600μm	SI	InP	

Table 2: Lattice matched InGaAs/InAlAs/InGaAs on InP substrate for 4-barrier HBV.

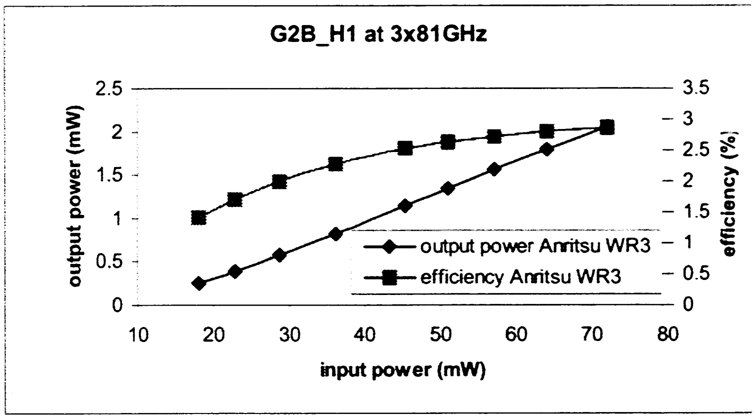

Fig. 5: Output power and efficiency of an 81/243GHz frequency tripler with a 4-barrier discrete planar HBV.

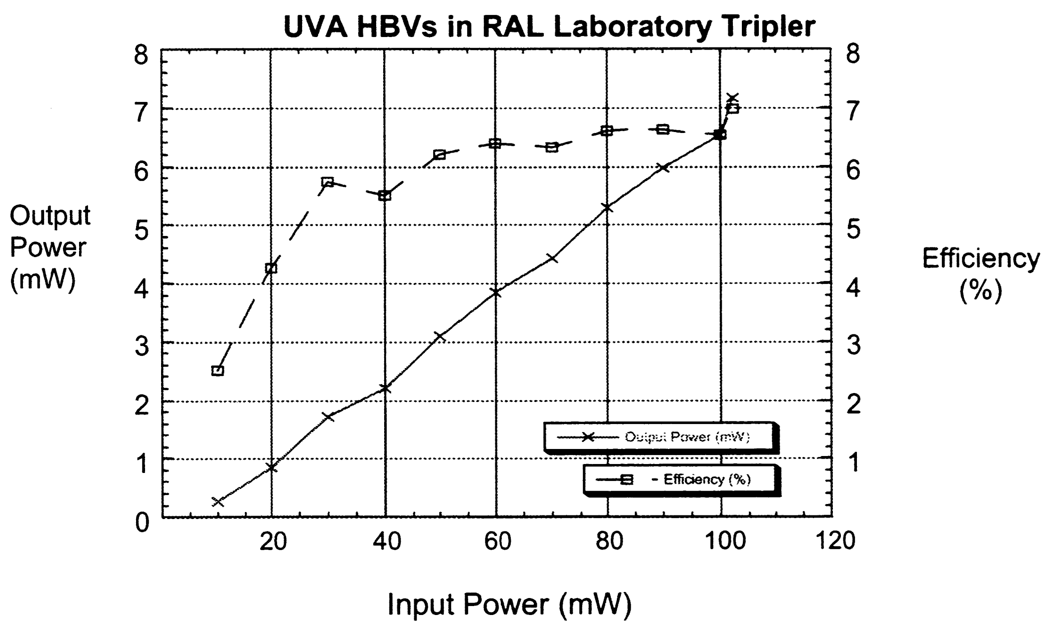

Fig. 6: Output power and efficiency of an 82/246GHz frequency tripler of RAL lab using UVa 4-barrier discrete planar HBV.

D. Four-Barrier-Integrated-HBV Frequency Triplers

In the previous batch of discrete 4-barrier HBV frequency triplers, the design with the smallest modulation mesa size had the best efficiency and the efficiency was still not saturated at the maximum input power. In the integrated version, several variations were included with smaller modulation mesa sizes.

A frequency tripler was very easily assembled by bonding an integrated HBV circuit into the channel of the block with glue. The RF test data is shown in Fig. 7. This result is on par with the best reported HBV frequency tripler at the same frequency [6].

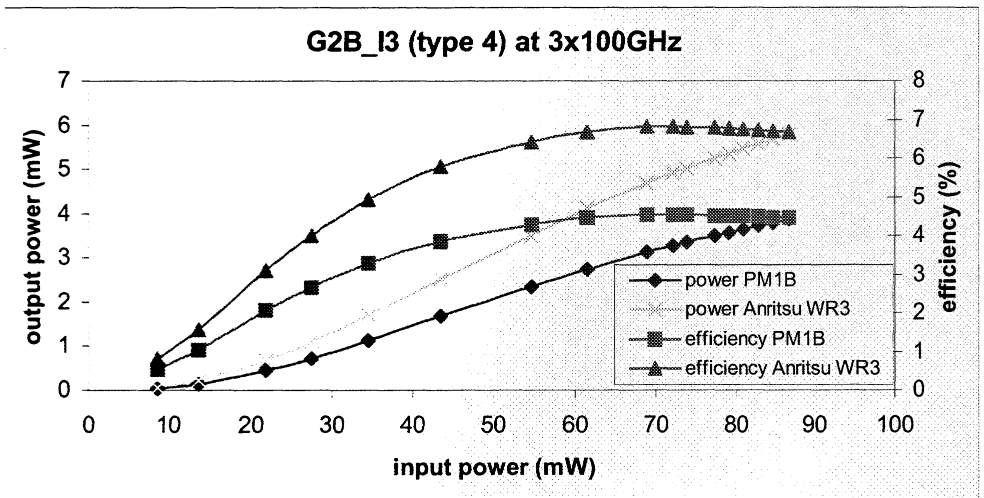

Fig. 7: Output power and efficiency of a 100/300GHz integrated 4-barrier HBV frequency tripler.

E. Output Fix-Tuned Integrated HBV Frequency Triplers

Encouraged by the results from the previous run of integrated HBV frequency triplers, we attempted to improve the performance further by adding a tuning circuit in the output matching network of the quartz circuitry. To make sure that we achieve the right impedance target, many variations of tuning circuits were designed. Also, modulation mesas have just one size which is a little larger than the best performer from previous integrated batch. However, the RF test results were only improved marginally. We believe the reason is that the output matching for previous untuned integrated version may be already good enough.

IV. CONCLUSION

Discrete and integrated HBV frequency triplers to WR-3 waveguide were designed, fabricated and tested. Integration significantly improved the tripler performance and reliability because of the better alignment, lower parasitic capacitance and easier assembly. Output power of 3.87 mW and efficiency of 4.5% at 300 GHz were measured with an Erickson PM1B power meter (about 6mW on with an Anritsu WR-3 meter). This tripler can be a good LO source for a heterodyne receiver or a good input source for another multiplier to higher frequencies.

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