GaAs/AlGaAs Multiquantum Well Structures Applied to High Frequency IMPATT Devices

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ABSTRACT

The first CW operation of GaAs/AlGaAs multiquantum well IMPATT devices at 100 GHz has been achieved. Multiquantum wells were used to generate the avalanche injection current since these structures improve the nonlinearity of the avalanche process and reduce the ionization rate saturation limitations. The operation and design principle, fabrication procedure and experimental results are presented in this paper. A 6.4 mW CW power output was achieved at 100.3 GHz.

I INTRODUCTION

A high frequency high power semiconductor source is the key element for many millimeter-wave systems. Up to this date, IMPATT (IMPact ionization Avalanche Transit Time) devices have been the most powerful solid state and convenient high frequency sources for the frequency range of 50-100 GHz. Conventional GaAs IMPATT devices show a quick fall-off in efficiency at the frequencies above 50 GHz because of the saturation of the ionization rates at high electric fields. Recently, multiquantum well structures have been proposed to reduce the ionization rate saturation limitations[1]-[3]. Efficiencies of 13% at 100 GHz and 10% at 140 GHz were projected for GaAs/AlGaAs single-drift flat-profile multiquantum well IMPATT devices[3]. In this paper, we report the first CW operation of GaAs/$Al_{0.3}Ga_{0.7}As$ multiquantum well IMPATT devices at 100 GHz. Preliminary results yielded 6.4 mW CW power at 100.3 GHz and 364 mA bias current in a non-optimized circuit. Experimental efforts are underway to optimize the circuit parameters and significantly higher powers are anticipated.

II OPERATION PRINCIPLE

For a high frequency operation, an IMPATT device must be biased at high electric fields. The saturation of ionization rates at high electric fields results in a broaden injected current pulse in a less localized avalanche region and degrades the device efficiency[4]. By replacing the bulk avalanche region by a GaAs/AlGaAs multiquantum well structure, the ionization rate saturation limitations can be reduced. Consider the case of an undoped GaAs/AlGaAs multiquantum well structure under an electric field. When an electron (hole) enters the wide bandgap material, it gives up some energy to the band discontinuity and encounters a higher ionization threshold energy. Therefore, it can accelerate to a higher energy without impact ionization and energy relaxation in the barrier region, as long as the barrier thickness is less than the energy relaxation length. In other words, an electron (hole) starts from a non-zero energy to reach the ionization threshold energy when the electron (hole) exits the barrier and enters the well. The non-zero starting energy for impact ionization increases as the electric field is higher. The periodic property of a multiquantum well structure serves as a constant supply for the non-zero starting energy. Thus, the effect of a multiquantum well structure is to reduce the effective ionization threshold energy. The effective ionization threshold energy (E'_T) for the multiquantum well structures can be expressed as $E'_T = E_T - E_0$, where E_T is the ionization threshold energy for the narrow bandgap material in a multiquantum well structure. The non-zero starting energy (E_0) can be expressed as follows: $E_0 = \Delta E + e\xi l_{eff}$. ΔE is the band discontinuity and $e\xi l_{eff}$ is the energy obtained from the potential barrier, where l_{eff} is the effective energy acceleration length and is equal to the smaller value of the two quantities, (1) energy relaxation length and (2) barrier length. In general, the energy obtained from the potential barrier is quite large in the high electric fields used for IMPATT devices applications at W-band frequencies (75-110 GHz). A carrier gains more energy from the potential barrier as the electric field becomes higher. Since a higher electric field leads to a stronger ionization rate enhancement, the ionization rate saturation limitations are reduced.

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Some trade-offs must be made in the design to take advantage of a multiquantum well structure. The well length should be long enough so that carriers from the barrier can ionize easily and gain enough energy to get out of the well. On the other hand, if the well length is too long, bulk type impact ionization can occur. The length of the barrier layer should be long enough so that carriers can gain enough energy from the electric field to improve the saturation of the ionization rates. However, the barrier layer length should not be too long such that impact ionization can occur in the barrier region. From our estimate, the optimal length for both barrier and well length should be between $100\AA$ and $200\AA$ for IMPATT devices at W-band frequencies.

III DESIGN & FABRICATION

A single-drift flat-profile multiquantum well IMPATT device was designed and the epitaxial layer structure in figure 1 was grown by MBE on a p^+ (Zn doped) GaAs substrate. The ingot where the p^+ substrate came from has the doping density of $7 \times 10^{18}/cm^3$ at the front of the ingot and $2 \times 10^{19}/cm^3$ at the tail of the ingot. The structure in figure 1 has a $2500\AA$ thick active layer which is approximately composed of a 40% avalanche injection region and a 60% transit time drift region. Thee avalanche injection region consists of five periods of quantum wells ($100\AA$ barrier length and $100\AA$ well length). The transit time drift angle ($0.75\ \pi$) at 100 GHz is close to optimal when the electron saturation velocity is 4×10^6cm/sec at 500 K. The active layer doping densities of $2 \times 10^{17}/cm^3$ for GaAs layers and $1.4 \times 10^{17}/cm^3$ for $Al_{0.3}Ga_{0.7}As$ layers were designed for the simple growth condition of a constant Si flux rate in an MBE system.

The room temperature I-V curve in figure 2 for the structure in figure 1 shows the desired hard breakdown at 10 V. The occurrence of avalanche breakdown is evident from the fact that breakdown voltage becomes smaller when the device is cooled down to 77 K. The device operates in an IMPATT mode instead of a MITATT (MIxed Tunneling Avalanche Transit Time) mode because the operating current density is at least six order magnitude larger than the maximum leakage current density ($10^{-2}A/cm^2$). A 7 V punch through voltage was obtained from a C-V measurement and agrees well with the designed structure. From both I-V and C-V measurements, the device has at least 30% voltage amplitude modulation when the device oscillates.

The key consideration in the fabrication of high frequency high power device is to dissipate the heat and reduce the series resistance from the substrate. A flip chip configuration with the junction side close to a dia-

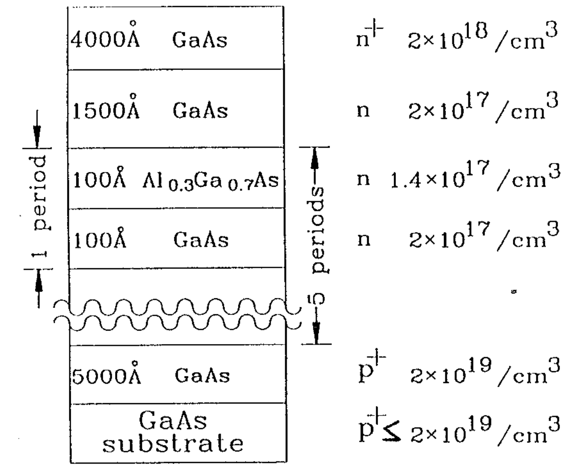

Figure 1: Multiquantum well IMPATT device epitaxial layer structure.

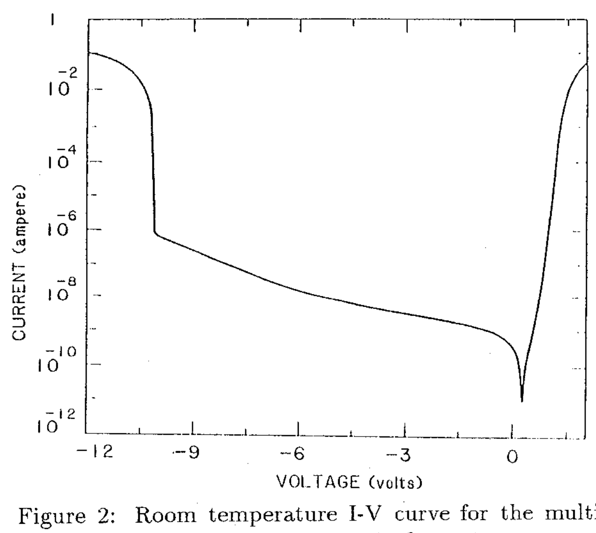

Figure 2: Room temperature I-V curve for the multiquantum well IMPATT structure in figure 1

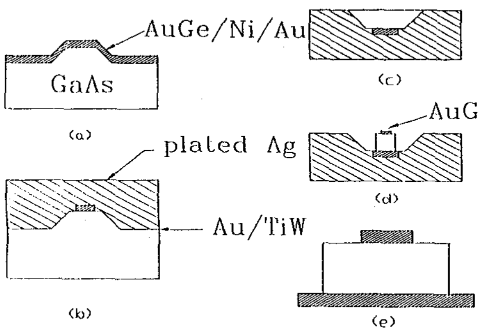

Figure 3: Diamond heat sink process.

mond heat sink can remove heat efficiently. The ohmic loss caused by the remaining substrate is enhanced by the skin effect at high frequency and needs to be minimized by thinning the wafer to several microns at 100 GHz. Thus, a novel wafer-thinning fabrication technique suitable for GaAs material has been developed to fabricate the multiquantum well IMPATT devices. A schematic cross-sectional view of a diode during the process is given in figure 3. The fabrication sequence is: (a) epitaxial side mesa etching and ohmic metal metallization, (b) epitaxial side pattern definition and heat sink plating, (c) wafer thinning from substrate side, (d) substrate side pattern definition and mesa etching and (e) diode separation. The mesa etching in step (a) is used as a thickness gauge in step (d) and determines the final device thickness. A thick layer of silver (75μm) was electroplated on the epitaxial side of the wafer in step (b) before the wafer was chemically thinned down from the substrate side to facilitate the handling of this thin wafer for the rest of the fabrication process. The TiW layer prevents the interdiffusion between Au and Ag for the rest of the fabrication process. After the wafer was chemically thinned down, circular AuGe/Ni/Au metal patterns and mesas were then also defined on the substrate side of this thin wafer in step (d). $H_2SO_4 : H_2O_2 : H_2O$ etching solutions of various compositions were used for mesa etchings and wafer thinning. The devices were alloyed at 450 °C for 30 seconds on a hot plate. The device separation was done by dissolving the silver shim in a nitric acid solution. The selective heat sink plating scheme for device separation is compatible with a hermetic pill type of packaging process. A diode after the separating step is 10μm thick and has AuGe(900Å)/Ni(150Å)/Au(1μm) on both sides.

The diode is T.C. bonded on a diamond heat sink and then packaged inside a 5 mil thick quartz ring (18 mil inner diameter and 30 mil outer diameter). A triple-strap ribbon connects one end of the diode to the quartz ring.

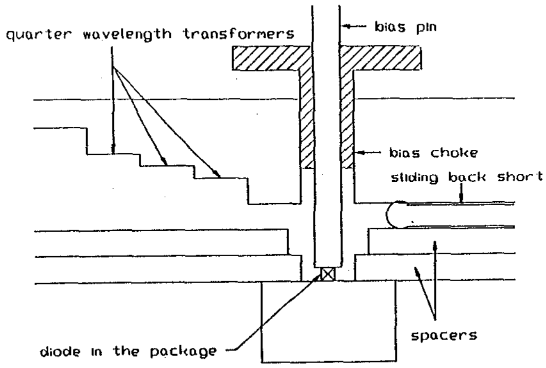

Figure 4: Kurokawa-type waveguide oscillator circuit.

Inside the package the ribbon prevents the top contact metal from shorting to the ground, the device area is adjusted by the trim procedure to have approximate 1 pf at zero bias for r.f. testing. The heat flow resistance measured is about 47 °C/W.

IV RF RESULTS

A Kurokawa type oscillator circuit as shown in figure 4 was incorporated in a W-band (75-110 GHz) reduced height waveguide (10 mil in height). The reduced height waveguide impedance was transformed to the full height waveguide impedance by a Chebyshev transformer formed by three quarter-wavelength reduced height waveguide sections. The coax sections of a Kurokawa circuit were formed by a bias pin and small holes in the shims. A backshort plunger and a cross-coupled r.f. choke coax section tune out the undesired reactance caused by the waveguide/coax junction. A slide fit mechanical design for the r.f. choke allows the r.f. choke to move freely. An anodized r.f. choke provides D.C. isolation and also prevents high frequency power leakage to the bias line. For additional tuning ability, an E-H tuner was placed after the oscillator circuit and followed by a simple microwave measurement set-up. The spectrum of an oscillator was measured by a heterodyne detection technique and figure 5 shows the spectrum of a CW multiquantum well IMPATT oscillator at 101.3 GHz. Oscillation frequency and r.f. power can be directly read from a wavemeter and a calibrated thermistor power meter. CW oscillation at 100.3 GHz has been obtained with 6.4 mW at 364 mA bias current for a diode under test and the output power and oscillation frequency as a function of the bias current is illustrated in figure 6. Devices tested in a pulsed mode showed oscillation at 94 GHz with power of 127 mW and 2.2% efficiency.

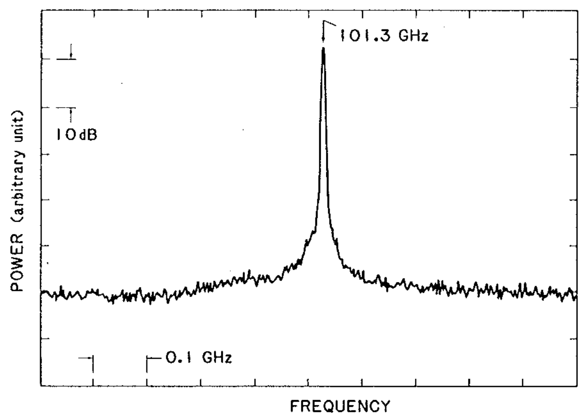

Figure 5: Spectrum of the CW multiquantum well IMPATT diode at 101.3 GHz with 3 MHz resolution bandwidth.

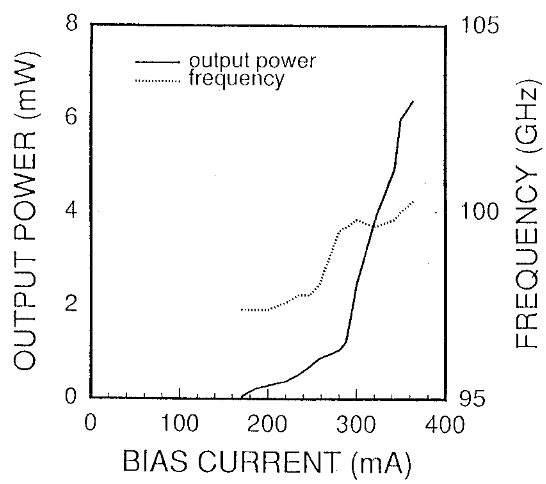

Figure 6: Output power and oscillation frequency as a function of the bias current for a CW multiquantum well IMPATT oscillator.

V CONCLUSION

In conclusion, a device fabrication process, a design idea and the performance of GaAs/$Al_{0.3}Ga_{0.7}As$ multiquantum well IMPATT devices at W-band frequencies was described in detail. No attempt has been made to optimize the device-circuit impedance matching and with further improvement in impedance matching higher powers are expected. Furthermore, the multiquantum well IMPATT structure in figure 1 is probably not an optimal design. Multiquantum well IMPATT devices with different well length, barrier length and barrier height will be investigated in the near future to find the optimal structure. Because the degree of saturation in ionization rates is less in multiquantum well structures, either a hi-low or low-hi-low Read type design can be used for the purpose of efficiency optimization. The output power and efficiency can be further improved by using a double-drift type design. The CW and pulsed operation of GaAs/AlGaAs multiquantum well IMPATT devices at frequencies around 100 GHz opens up a new field for the applications of modern epitaxy technologies to two terminal high frequency sources.

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