MILLIMETER-WAVE DOUBLE-DRIFT HYBRID READ PROFILE Si IMPATT DIODES*

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ABSTRACT

Double-drift Si IMPATT diodes with hybrid Read profiles were designed, fabricated and tested for millimeter-wave frequency operation. Vapor phase epitaxy (VPE) growth was used to achieve well controlled abrupt n-type doping transitions. We achieved 1.95 W with 11.7 percent efficiency at Q-band (40.6 GHz). At V-band, we achieved 1.05 W with 13.6 percent efficiency (61 GHz) and an injection locked amplifier achieved 20 dB gain, 800 mW and 2 GHz bandwidth with greater than 10 percent efficiency. Finally, at W-band, we achieved 612 mW with 5.7 percent efficiency (93 GHz) and for long pulse operation 1.08 W peak power at 96 GHz.

INTRODUCTION

Over the past ten years, progress in millimeter-wave Si IMPATT diodes has been slow as compared to GaAs IMPATTs. This is due to the extensive use of MBE technology for realizing double Read and hybrid Read profiles for GaAs IMPATT devices. Computer simulations show that silicon IMPATTs with similar profiles can also achieve high efficiency (1). This has motivated us to pursue Si IMPATT technology. Recently, Si MBE IMPATT diodes with double-drift flat profiles demonstrated 600 mW at 90 GHz, however, junction temperature was high (2). Si MBE technology is not mature and has inherent difficulties such as low wafer throughput and high system complexity which limits its use for Si IMPATT profile growth. An attractive alternative is vapor phase epitaxy (VPE), which is inexpensive, has high throughput and can achieve good uniformity across multiple wafers in a single growth run. This paper will present results for millimeter-wave Si IMPATT diodes fabricated with VPE technique to realize hybrid Read profiles. Excellent RF performance for Q-, V-and W- bands were achieved with low junction temperatures.

PROFILE DESIGN CONSIDERATIONS AND MATERIAL GROWTH

Figure 1 shows a doping configuration for a double drift hybrid Read structure. The pn junction is located between the uniformly doped p-type layer and the highly doped n-type region. The n-drift region is uniformly doped. The doping level was selected to allow the diode electric field punch through occur at dc breakdown to minimize RF loss and to narrow the avalanche region. The thickness of the active region was based on transit time considerations. Relaxation time effects also influence the design parameters of millimeter-wave devices.

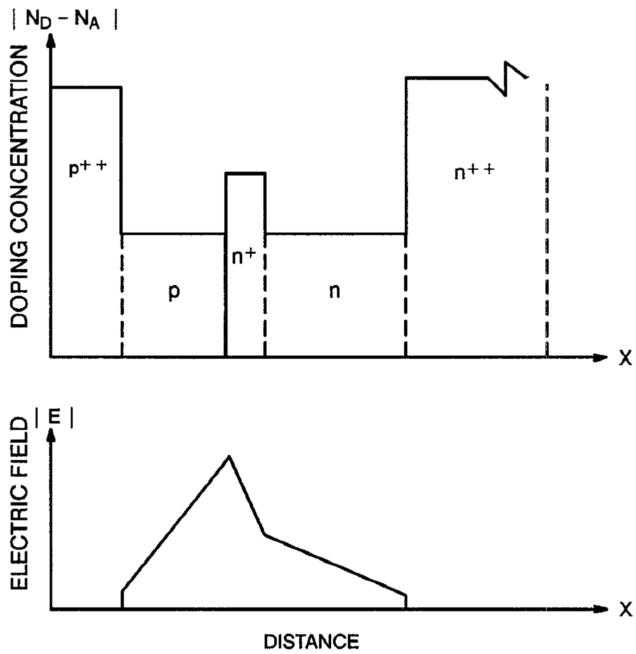

Figure 1 Doping and electric field profile of double-drift hybrid read structure.

We initially grew hybrid Read structures using atmospheric pressure vapor phase epitaxy. The major difficulty in using VPE for growing hybrid structures is in controlling the process to obtain the very abrupt doping transitions required for the N^+ spike region of the profile. Our efforts to achieve this involved optimization of the growth process by minimizing gas residence time in the reaction chamber and lowering the silicon growth rate during deposition of the n-dopant spike. By using a growth rate of 500 Å/min, we were able to grow a sharp transition dopant spike of around 0.2 μm thickness in a

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repeatable manner for both V-band and Q-band profiles. For W-band, it was desirable to obtain even thinner N^+ doped spike layers since the total N^+ and N region was approximately 0.3 μm thick. However, due to diffusion of the N^+ dopant during the growth sequence, it was difficult to grow spike regions thinner than 0.2 μm. This imposes a limitation on achieving high performance W-band hybrid Read IMPATT diodes. Figure 2 shows a SIMS profile for a typical V-band profile. A sharp doping transition between N^+ and N can be seen from this figure. W-band profiles did display N^+ spike characteristic despite significant N^+ diffusion. The P^+ layer was formed by thermally diffusing boron into the epi-wafer.

DEVICE FABRICATION

Silicon epi-wafers were thinned to 5 to 10 μm from backside using wet chemical bubble etching for reducing series resistance which can degrade the diode RF performance. The thinned wafer was then metallized on both sides. The front epitaxial side was metallized with Cr-Pt-Au, while the backside was metallized with Cr-Au. Single mesa pill-type diodes were formed by etching unwanted metal and silicon. The diode was then placed on a metallized diamond heat sink with a ceramic ring. Finally, a cross gold strap was thermocompression bonded to the diode and the ring.

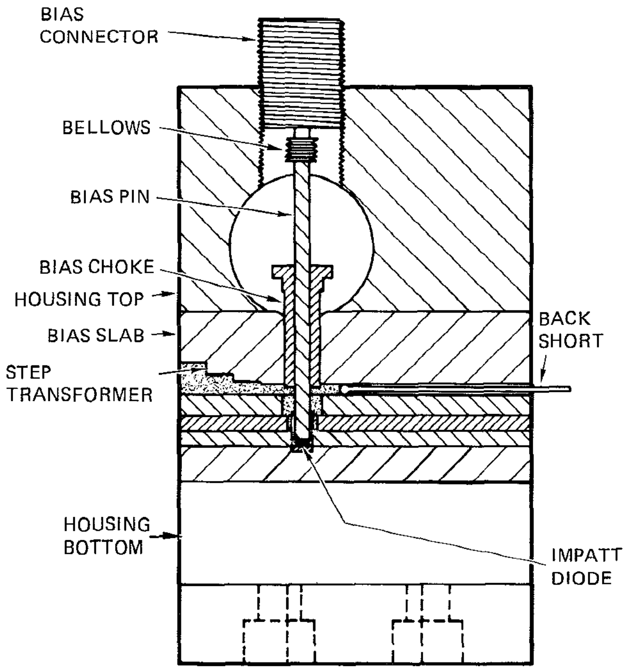

Figure 3 Coaxially-coupled reduced-height waveguide circuit.

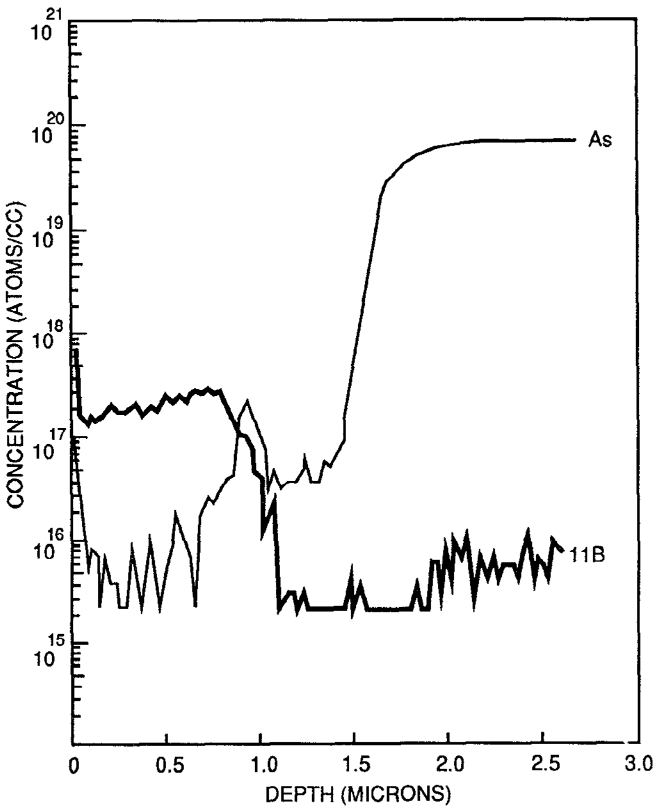

Figure 2 SIMS profile of a V-band hybrid Read profile grown using VPE techniques. Excellent transition between N^+ and N can be observed.

RF MEASUREMENT

The RF performance of millimeter-wave double drift hybrid Read silicon IMPATT diodes were evaluated in a coaxially coupled reduced-height waveguide cavity shown schematically in Figure 3. The fixture provides a great versatility in impedance matching.

Table 1 summarizes the best RF performance for silicon hybrid Read IMPATT diodes. Our Q-band diode achieved the highest conversion efficiency of 11.7 percent at 40.6 GHz with 1.95 W output power. Our V-band diode achieved an efficiency of 13.6 percent at 61.1 GHz with 1.05 W, measured at the output of cavity. However, while tuning for power, our V-band diode achieved even higher power level of 1.35 W with 12.5 percent efficiency at 61.5 GHz. These results are better

TABLE 1
SUMMARY OF MILLIMETER-WAVE Si HYBRID READ IMPATT RF PERFORMANCE

Zero Bias Capacitance (pF)	Oscillation Frequency (GHz)	Estimated Output Power (W)	Estimated Junction Temp. Rise (°C)
1.85	40.6	1.95	220
1.35	61.1	1.05	172
1.60	93.0	0.612	200

than that of GaAs IMPATTs at the same frequency (3). For W-band, we achieved an output power of 612 mW with 5.7 percent efficiency at 93 GHz. The estimated junction temperature rise was around 200°C. This result is better than uniform profile diode results at the same junction temperature rise (2,4). Figure 4 shows the performance of the W-band diode as a function of dc bias current. We operated a W-band diode in a long pulse condition. The pulse width was 10 μs and the duty cycle was 33.3 percent. The diode delivered a peak power of 1.08 W at 96 GHz at a peak current of 900 mA. The efficiency was around 5.9 percent and the estimated junction temperature rise was less than 350°C.

The silicon VPE grown IMPATT diodes, especially V-band diodes, exhibited an excellent performance in injection locked amplifier and stable amplifier applications. Figure 5 shows the performance of a V-band single stage injection locked amplifier. A gain of 20 dB has been achieved for this amplifier with locking bandwidth of greater than 2 GHz. The output power was 800 mW with an efficiency of greater than 10 percent. This performance makes these V-band diodes very attractive for power combining applications. Figure 6 shows the performance of a V-band single stage stable amplifier. The amplifier achieved 4.5 dB gain and 1.2 W output power with 2 GHz bandwidth.

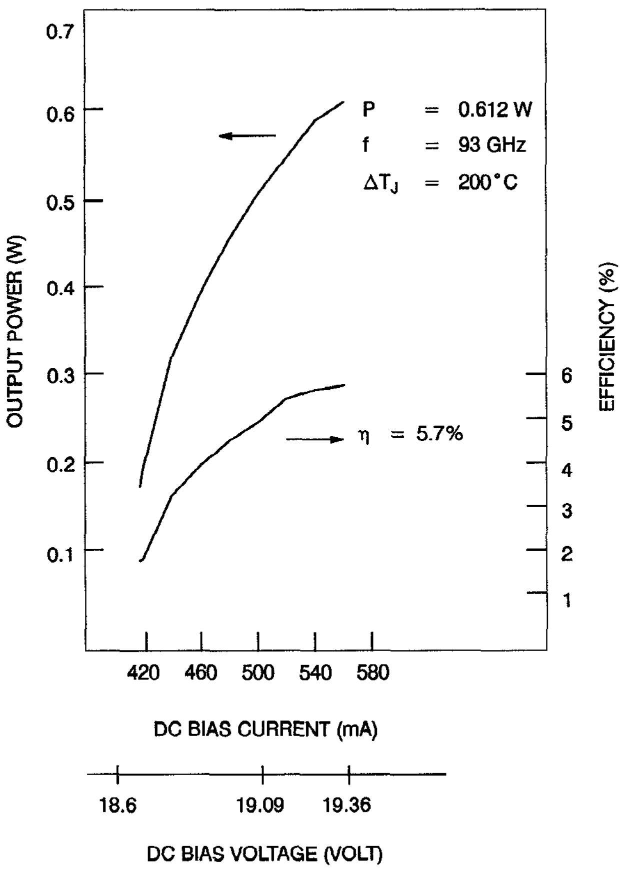

Figure 4 Performance of a W-band Si hybrid Read IMPATT oscillator.

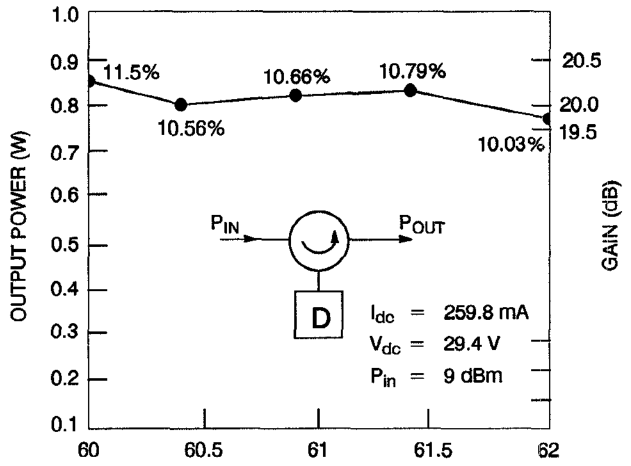

Figure 5 Performance of a V-band single stage IMPATT injection locked amplifier.

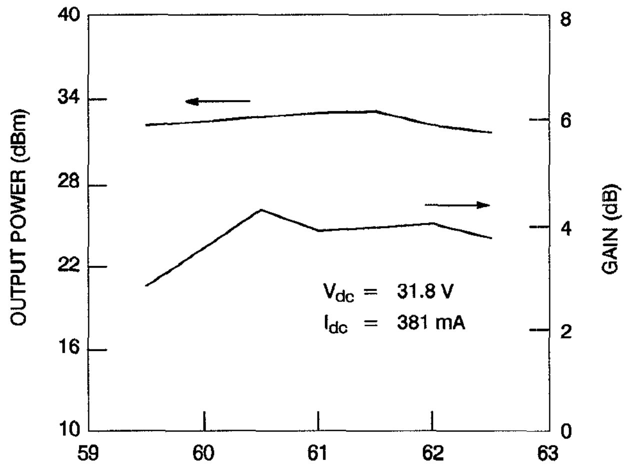

Figure 6 Performance of a V-band single stage IMPATT stable amplifier.

CONCLUSION

We successfully grew double-drift hybrid Read structures for millimeter-wave silicon IMPATT diodes using atmospheric pressure VPE with an optimized growth process. Significant CW performance has been achieved for Q-, V- and W-band diodes. The efficiencies of 11.7 percent, 13.6 percent and 5.7 percent has been measured respectively. A W-band diode in long pulse operation achieved 1.08 W peak power with a pulse width of 10 μs. V-band diodes were especially suitable for injection locked amplifier and stable amplifier applications. A 20 dB gain, 800 mW in a 2 GHz bandwidth with more than 10 percent efficiency has been achieved for a V-band injection locked amplifier. This makes these devices very attractive for power combining applications. A V-band stable amplifier achieved 4.5 dB gain with 1.2 W output power.

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