Design, Fabrication and Evaluation of Tunnel Transit-Time Diodes for V-Band and W-Band Power Generation

C. Kidner, H. Eisele, J. East and G. I. Haddad

Solid-State Electronics Laboratory

Department of Electrical Engineering and Computer Science

University of Michigan, Ann Arbor, Michigan, 48109-2122

ABSTRACT: TUNNEl injection Transit-Time (TUNNETT) diodes are very promising for medium power, low noise applications up to THz frequencies. We have successfully designed and tested GaAs $p^+n^+n^-n^+$ single-drift TUNNETT diodes for V-band and W-band operation. We have measured 26 mW at 58.0 GHz and 33 mW at 93.5 GHz with good spectra.

TUNNEl injection Transit-Time (TUNNETT) diodes are a promising technology for low noise, medium power millimeter and submillimeter wave sources. The tunneling process is very fast and localized, and thus TUNNETT diodes are expected not to show the high frequency electronic limitations of IMPact ionization Avalanche Transit-Time (IMPATT) diodes. The tunneling process is also relatively quiet, making TUNNETT diodes a prime candidate for low noise applications. Pulsed oscillations have been demonstrated up to 338 GHz [1]. Recently advances in MBE techniques have been exploited to obtain promising CW power from devices with low impact ionization carrier multiplication [2].

We have successfully designed and tested $p^+n^+n^-n^+$ single-drift TUNNETT diodes for V-band (50-75 GHz) and W-band (75-110 GHz) operation. The basic structure and electric field profile of the device is given in Figure 1. Both designs operated within the range of frequencies expected. The V-band devices produced 26 mW at 58 GHz with 1.4 % efficiency. The W-band devices produced 33 mW at 93.5 GHz with 2.65 % efficiency. The oscillations have a clean spectrum. W-band GaAs IMPATT devices have demonstrated very low noise operation [3]. Tunneling is expected to be a much quieter injection mechanism than impact ionization, resulting in a device with still lower noise levels. TUNNETT diodes are very promising for medium power, low noise applications up to THz frequencies [4].

The layer sequences for the V-band and W-band designs are shown in Figure 2. The design of the structure

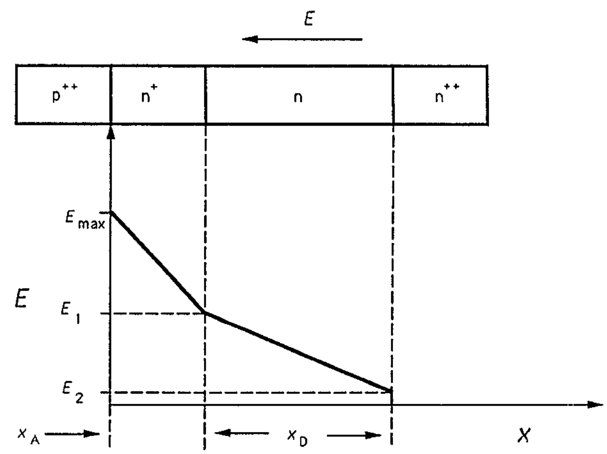

Figure 1: Nominal Structure and Electric Field Profile of a $p^{++}n^+n^+n^{++}$ single-drift TUNNETT Diode

was based on experimental studies of highly doped MBE grown $p^{++}n^+$ junctions. The p^{++} doping is as high as the available technology allows in order to give a one sided junction. The n^+ doping is a trade off between avoiding impact ionization and a backward diode. The length of the n^+ region is to give the proper field at the beginning of the drift region. The drift region was designed to have a length of $3\pi/4$ at the nominal operating frequency using a drift velocity of 4.6×10^6 cm/s at 500 K and high fields [5, 6]. The doping level in the drift region is a trade off between avoiding impact ionization and space charge effects while maintaining fields sufficient for saturated drift velocity. The $Al_{.55}Ga_{.45}As$ layer allows the GaAs substrate to be removed using a selective etch process.

The devices were fabricated from MBE grown material. Evaporated Ti/Pt/Au was used for the p-ohmic contact. Gold was electroplated onto the p-ohmic to create an integral heat sink and to provide mechanical strength. The GaAs substrate and the $Al_{.55}Ga_{.45}As$ layer were removed with two different selective etches to minimize

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PROFILE	DOPANT	V-BAND		W-BAND	
		THICKNESS	$\|N_d - N_a\|$ (cm^{-3})	THICKNESS	$\|N_d - N_a\|$ (cm^{-3})
P^+ GaAs	Be	6000 Å	5.0×10^{19}	2400 Å	5.0×10^{19}
N^+ GaAs	Si	420 Å	2.5×10^{18}	400 Å	3.0×10^{18}
N^- GaAs	Si	7500 Å	2.9×10^{16}	3000 Å	7.3×10^{16}
N^+ GaAs	Si	10000 Å	5.0×10^{18}	15000 Å	5.0×10^{18}
N^+ $Al_{.55}Ga_{.45}As$	Si	6000 Å	5.0×10^{18}	6000 Å	5.0×10^{18}
N^+ GaAs	Si	10000 Å	5.0×10^{18}	2500 Å	5.0×10^{18}
Substrate	—	—	—	—	—

Figure 2: Nominal Doping Profiles for V-band and W-band TUNNETT Diodes.

series resistance to the device. The n-ohmic contact was formed using evaporated Ni/Ge/Au/Ti/Au. A second lithography process gave holes through which 3μm of gold was electroplated on the n-ohmic contact in order to ease bonding. The mesa was then created using a standard wet etch. The sample was diced and the diodes were mounted on gold plated copper blocks. Two tapered leads were bonded to four quartz stand offs and to the diode. The copper block forms the bottom wall of a resonant cap, full height waveguide cavity optimized for IMPATT devices [7].

The DC I-V characteristics of the devices clearly demonstrate that the injection mechanism is predominantly tunneling. Figure 3 shows the I-V curve of a 25 μm diameter W-band diode at room temperature and at 200 °C. For comparison the I-V curve of a 55 μm V-band MIxed Tunneling and Avalanche Transit-Time (MITATT) diode is also given in Figure 3. At room temperature the MITATT diode has a sharp increase in current at about 18 V. This behavior is expected and is due to the onset of impact ionization [8]. The TUNNETT diode I-V curve exhibits no sign of this behavior. Tunneling as the dominant breakdown mechanism also explains the temperature dependence of the TUNNETT diode I-V curve. Increasing the temperature of the device enhances tunneling and suppresses impact ionization as can be seen in the MITATT diode temperature behavior. For low bias the current increases, indicating tunneling. The sharp increase in current has a positive temperature coefficient, characteristic of impact ionization. For the measured range of bias the current in the TUNNETT diode always increases as a function of temperature implying that impact ionization is not significant.

The preliminary high frequency measurements demonstrate that TUNNETT diodes are a useful millimeter wave source. With the V-band devices we have measured 26 mW at 58.0 GHz with 1.4 % DC to RF conversion efficiency and 26 mW at 60.9 GHz with 1.5 % DC to RF conversion efficiency. The performance of six W-band TUNNETT diodes is given in Table 1.

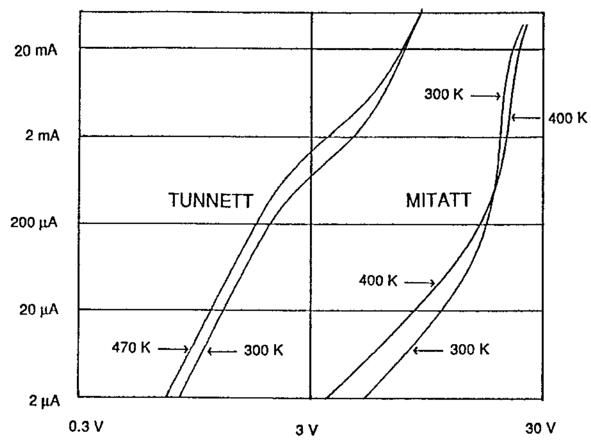

Figure 3: Reverse bias Current-Voltage characteristics for pure tunnel injection (TUNNETT) and mixed tunnel injection and impact ionization (MITATT) at room temperature (300 K) and at elevated temperatures (470 K and 400 K, respectively).

FREQUENCY	MAXIMUM POWER	EFFICIENCY
87.22 GHz	27 mW	1.75 %
93.50 GHz	33 mW	2.65 %
102.50 GHz	29 mW	3.20 %
107.30 GHz	31 mW	3.35 %
111.25 GHz	14 mW	2.35 %
112.50 GHz	16 mW	2.55 %

Table I
Performance of Different W-band TUNNETT Diodes

The power, efficiency and frequency of a W-band TUNNETT diode as a function of DC current is given in Figure 4. Neither the power nor the efficiency has saturated at the current levels tested. The measured spectrum of the free running W-band oscillator is shown in Figure 5. Using a self-injection locking method we determined the loaded Q of the W-band cavity to be 170. The spectrum of the free running V-band oscillator is shown in Figure 6.

TUNNETT diodes have demonstrated practical power levels and oscillation spectra as V-band and W-band sources. Further work, including optimization of the circuit for TUNNETT diode operation and using a diamond heat sink, is expected to increase the performance of the devices. The technology developed for these frequency ranges will be useful in the design and realization of TUNNETT diodes for still higher frequencies.

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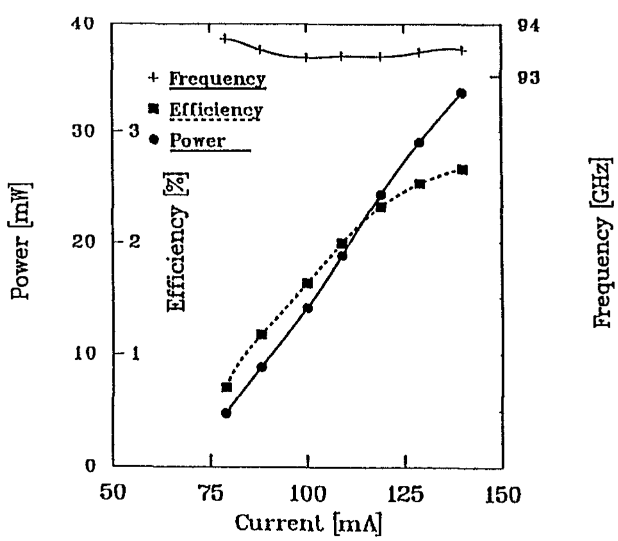

Figure 4: Output power, frequency and efficiency as a function of bias current for a W-band TUNNETT diode.

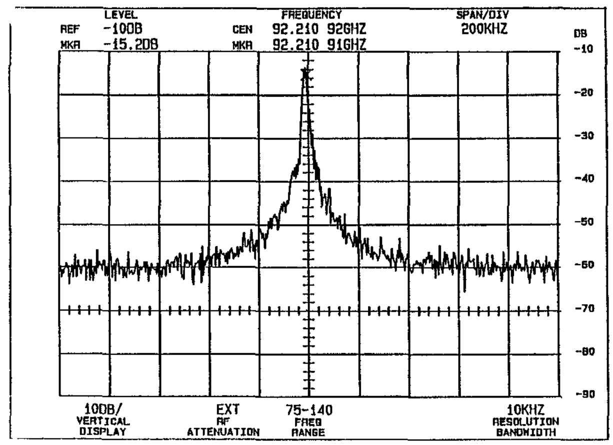

Figure 5: Spectrum of a W-band TUNNETT diode free running oscillator. Power level: 9.2 mW. Center frequency: 92.21 GHz. Vertical scale: 10 dB/div. Horizontal scale: 200 kHz/div. BW: 10 kHz

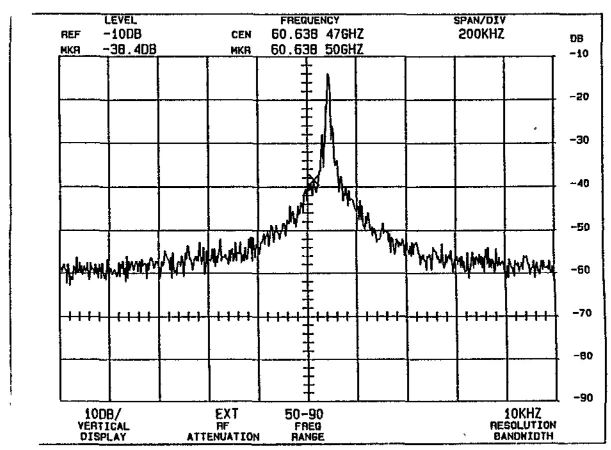

Figure 6: Spectrum of a V-band TUNNETT diode free running oscillator. Power level: 6.3 mW. Center frequency: 60.64 GHz. Vertical scale: 10 dB/div. Horizontal scale: 200 kHz/div. BW: 10 kHz

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