Ballistic Tunneling Transit Time Devices for THz Power Generation

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Abstract

Existing transit time devices such as IMPATT and TUNNETT diodes are based on semiconductor structures. These devices have transit times and operating frequencies that are limited by the saturated velocity in the semiconductor material, the physics of carrier injection, the dielectric constant and the critical field for breakdown.. The combination of a transit time and a capacitive reactance that scales with frequency results in a power and frequency scaling law of the form $P_{rf} \times f^2 \propto C_{material}$, where $C_{material}$ is a constant that depends on the material parameters. An ideal device would have ballistic carriers and a relative dielectric constant equal to 1. This is the basis of the proposed Ballistic Tunneling Transit Time Device (BT^3D), a new transit time device with a vacuum drift region and a tunneling injector. The design and performance of this new device will be described in this paper.

I. Introduction

Local oscillator sources are a key component of submillimeter and THz systems. Fundamental semiconductor sources such as Gunn and IMPATT devices are available at lower frequencies. Harmonic multiplier chains using semiconductor varactor diodes can produce modest amounts of power at THz frequencies. Optical sources based on photoconductive mixing of two locked lasers are under investigation. Gas lasers, although large and complex, can produce milliwatts of power over the desired THZ frequency band. However, these existing sources have limitations for space based applications. The solid state electronic and optical sources do not yet produce enough power to pump Schottky diode mixers and barely produce the required power for HEB mixers. The gas lasers are too large and require too much prime power for space based applications. An alternative source is needed. In this paper we propose the Ballistic Tunneling Transit Time Device (BT^3D), a vacuum based alternative to conventional transit time devices. The device structure and dimensions will be discussed in the next section. Section III will describe a simple computer simulation to investigate the power and frequency characteristics of these new devices. Several micromachined approaches to the fabrication will be discussed in Section IV. A brief summary and conclusions will be given in Section V.

II. Ballistic Tunneling Transit Time Devices(BT^3D)

Conventional semiconductor transit time devices are limited by saturated velocities and carrier injection physics. The resulting tradeoff between available power and frequency is of the form $P_{available} \times f^2 \propto C_{material}$, where $C_{material}$ is a constant that depends on material parameters such as the saturated velocity, dielectric constant and critical electric field for breakdown. A vacuum is an ideal drift region with a carrier velocity that is ballistic rather than saturated, a relative dielectric constant of 1 and a very high breakdown field. This is the basis of the Ballistic Tunneling Transit Time Device (BT^3D) to be discussed in this paper. An ideal structure is shown in Fig.1 a. The device is a diode with a micromachined field emitter cathode, a drift region and a collecting anode, all sealed in a vacuum. This small structure is mounted across a waveguide as shown in Fig. 1 b. A voltage is applied through a bias circuit that provides RF isolation. The applied voltage combined with the device dimensions will set up an electric field across the drift region. If proper magnitude DC and RF fields are present at the cathode, field emission will occur at the cathode tips. These carriers will be accelerated across the drift region and collected at the anode. The acceleration and resulting transit time will depend on the applied voltage and the dimensions. With a proper design this transit time effect can produce RF power. The combination of the drift region length and the bias voltage will determine the operating frequency of the device. If we assume a transit time equal to the inverse of the frequency, then we can find the required voltage vs. drift region length for different frequencies. This is shown in Fig. 2. The voltages and dimensions for THz structures are within the ranges that can reasonably be fabricated with micromachining techniques.

The next step is to investigate the transit time characteristics of this ballistic

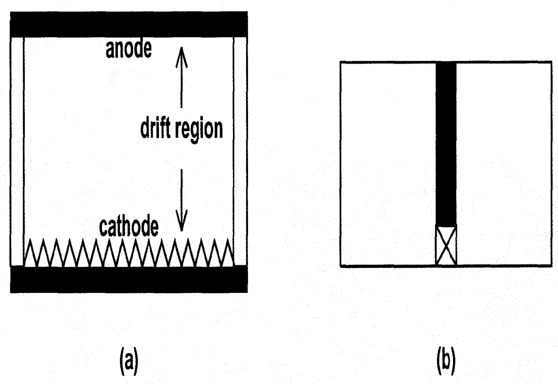

Figure 1: BT^3D (a) Structure (b) Waveguide Mount

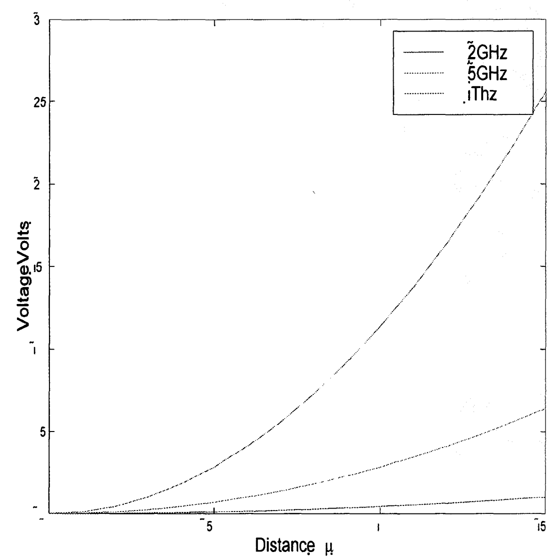

Figure 2: BT^3D Voltages and Transit Region Lengths for Different Frequencies

structure. An ideal semiconductor transit time device has carriers traveling at a constant saturated velocity. The resulting induced current waveform is rectangular, with a starting phase θ_{inj} at the injection angle and a width θ_d equal to the drift angle. The BT^3D carriers will have a constant acceleration so the resulting induced current is triangular, again starting at the injection angle θ_{inj} with a drift angle θ_d. This form of the device injected current can be used to estimate the available power and frequency response for various BT^3D designs. However, a more realistic analysis depends on the properties of the cathode injector.

The cathode is a field emitter with a current vs. voltage characteristic that depends on the electric field at the tip, the geometry of the tip and the preparation of the surface. The properties of the cathode are critical to the device performance. However, the basic form of the cathode current is an exponential dependence on the voltage or the cathode field, with the peak current occurring at the $\pi/2$ phase point. We can write a computer simulation to obtain the injected and induced currents for a range of RF conditions. The analysis is more complex than a corresponding semiconductor transit time device. In a semiconductor all the carriers within the drift region have the same velocity, and the induced current can be obtained by integrating over the charge within the device. For a BT^3D the carrier acceleration is constant and the velocity depends on the amount of time the carriers spend in the drift region. A double integration over time and injection angle is needed to obtain the induced current. A computer simulation has been written to investigate this problem. The simulation predicts the large signal induced current waveform of the device. The ratio of the Fourier components of the fundamental RF current and the RF voltage gives the device admittance. This, along with the RF voltage, the embedding impedance and the parasitic resistance gives the available power into a matched load. This information can then be used to investigate a variety of device structures, bias conditions and operating frequency ranges. Some example calculations will be discussed in the next section.

III. Example Performance Calculations

This section will describe BT^3D performance for a range of bias conditions and operating frequencies. However, before discussing the simulation results, it is interesting to look at a simple approximation for the device performance. The injected current waveform for constant DC current density and a varying RF voltage is shown in Fig. 3. Although the details of the injected current will depend on the physics of the cathode, the general form is a sinusoidal waveform at small RF voltages that quickly becomes a sharp pulse around $\pi/2$ for larger RF voltages. The resulting induced current waveform under sharp pulse operating conditions will have a fundamental Fourier component that is $\propto J_{dc}$ and is independent of the RF voltage. The device conductance, $G_{electronic}$, will be

$$G_{electronic} \propto \frac{J_{dc}}{V_{rf}}, \tag{1}$$

and the RF power will be

$$P_{rf} \propto G_{electronic} \times V_{rf}^2 \propto J_{dc} V_{rf}. \tag{2}$$

The available RF power depends on the DC current density and the RF voltage. From this approximate large signal model for BT^3D operation we can make some predictions about the power and frequency response that we can expect. First consider the small signal G-B plots for a BT^3D with a design center frequency of 1 THz operating over a frequency range between 700 and 1300 GHz with a DC current density between 100 and 500 A/cm^2. The corresponding small signal G-B plot is shown in Fig. 4. This figure shows many of the basic characteristics of this device. The device has a conductance that depends on the DC current density. Reasonable current densities will be needed to obtain useful powers and to match the device to an external circuit. Second, the device has a very broad bandwidth, 600 GHz in this case for a 1 THz center frequency. Finally, the device has an excellent -Q compared with conventional semiconductor transit time devices. The will allow easier matching and reduce the effect of parasitic resistance. The -Q value for the 500 A/cm^2 case is nearly 1. Next consider this device operating under large signal conditions. Large signal G-B curves for the device of Fig. 4 are shown in Fig. 5 for a device with a DC current density of 200 A/cm^2 and an RF voltage between 0.005 and 0.2 volts. This figure shows the effect of the sharp pulse injection on device operation with the device conductance decreasing with increasing RF voltage. This will effect the device impedance levels, area and output power.

In order to extract power from the device, the circuit impedance must conjugate match the device impedance. This condition sets the device area.

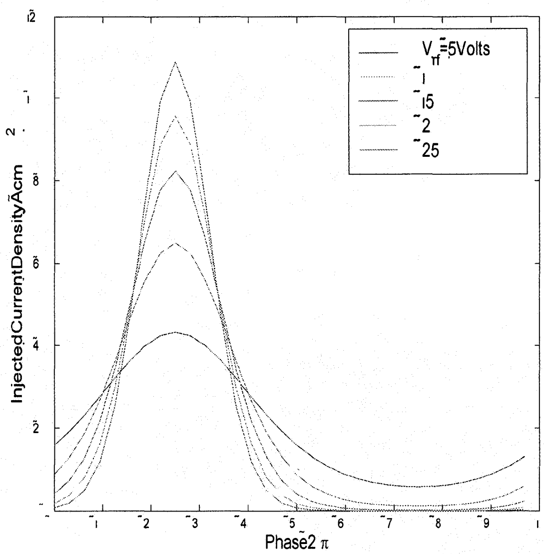

Figure 3: Example Injected Current Waveform

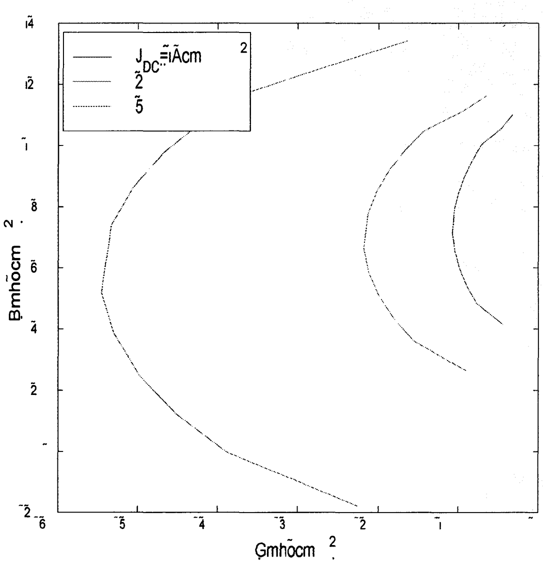

Figure 4: Small Signal G-B Plot, Frequency = 700-1300 GHz, J_{dc} = $100, 200, 500 A/cm^2$

Typical realistic circuit impedances are several Ω's. We must include the effect of parasitic loss to get a more realistic power prediction. If the load resistance is R_{load} and the parasitic resistance is R_s, then

$$-R_{device} = R_{load} + R_s, \tag{3}$$

where R_{device} is the real part of the device impedance obtained from the inverse of the device admittance including the device capacitance. The power into the load is

$$P_{load} = \frac{R_{load}}{R_{load} + R_s} P_{rf}. \tag{4}$$

We can use this equation along with the calculated device properties to estimate the available RF power. The properties of the device can best be investigated with a sample calculation. Consider a BT^3D with a design center frequency of 1 Thz, a DC current density of 1000 A/cm^2, a drift region length of approximately 0.7 μ and an applied DC voltage of 9.8 volts. We define the small signal admittance at an RF voltage value of 0.025 volts. The area of the device will depend on the external circuit matching resistance. Device areas for matching resistances between 0.5 and 5 Ω are shown in Fig. 6. This figure shows the effect of the higher electron velocity and lower dielectric constant on the device dimensions. This device has a much longer drift region and larger diameter, 20 to 50 μ, than a comparable frequency semiconductor device. This compensates for the lower current density, higher operating voltage and smaller V_{rf}/V_{dc} ratio to produce reasonable powers at THz frequencies. The available power into a matched load depends on the value of the matching resistance and the parasitic resistance. The estimated power for this device is shown in Fig. 7 for RF voltages between 0 and 0.5 volts and small signal load resistances of 1 to 3 Ω. The solid lines are the available power from the device and the dashed lines correspond to a parasitic resistance of 1Ω. This device is producing 2 mW at 1 THz, excellent performance for any electronic device at this frequency.. The low device -Q allows an increase in matching resistance at low RF voltages and reduces the parasitic resistance effect.

The device properties strongly depend on the DC and peak current density of the cathode. The variation in output power with RF voltage for a range of DC current densities is shown in Fig. 8. The device is operating at 1 THz. The load resistance is 3Ω and the parasitic resistance is 1Ω. This figure shows

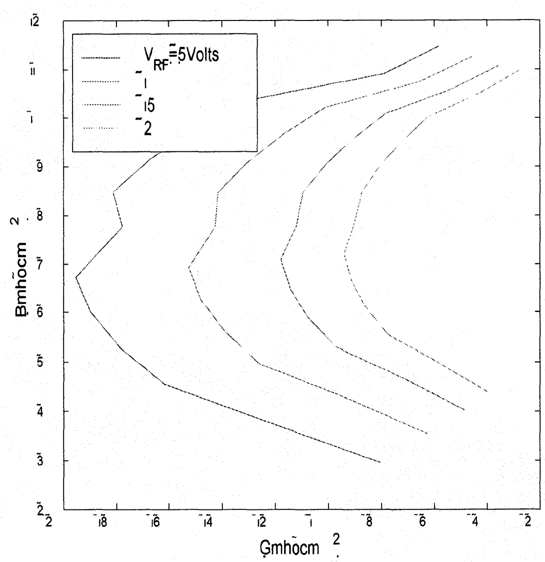

Figure 5: Large Signal G-B Plot, Frequency = 700-1300 GHz, J_{dc} = $200A/cm^2$, V_{rf} = 0.05,0.1,0.15,0.2 Volts

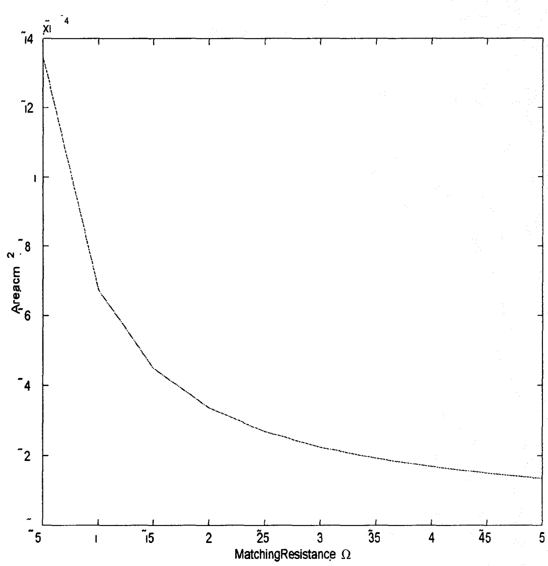

Figure 6: Small Signal Device Area $J_{DC} = 1000A/cm^2$

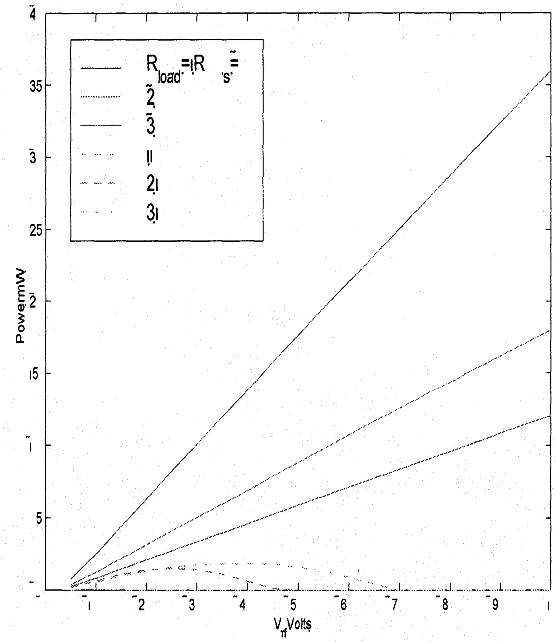

Figure 7: Output Power vs. V_{rf},Frequency = 1THz,J_{dc} = 2000 A/cm^2

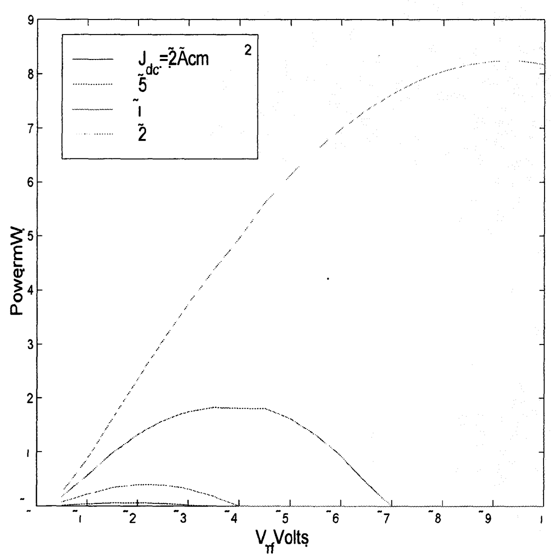

Figure 8: RF Power vs. RF Voltage for a Range of DC Current Densities,Frequency = 1 THz

the critical importance of current density on device performance. Increasing the DC current density increases the device negative conductance and the area required to match the load impedance. The combination produces nearly 10 mW of output power for a current density of $2000A/cm^2$, excellent performance for any electronic device at THz frequencies.

IV Device Design and Fabrication

The discussion in the first part of this report gave the design dimensions and operating conditions for the proposed BT^3D device. However it is also important to think about the design and fabrication of realistic device structures. A proposed device structure was shown in 1. This would be a vertical emitting structure with the electric field and drift region perpendicular to a planar cylindrical cathode. The critical properties would be the current vs. field characteristics of the cathode, the voltage across the drift region, the length of the drift region and the resonant frequency of the rest of the micromachined cavity. We would also need to couple energy out of the cavity and into a waveguide or quasi-optical coupling network. We would also need to provide DC isolation between the cathode or anode and the rest of the structure. An alternative approach would be to design and fabricate a horizontal emitter with the drift region defined on the same wafer as the cathode. It could be fabricated on the surface of a semi-insulating semiconductor or other support structure. The substrate is assumed to be semi-insulating. A backing conductor material, a thin cathode material and a second support material are deposited onto the substrate. A vertical etch can be used to expose the three layers on the cathode side of the device, and a second etch can be used to etch back the backing material, allowing a very thin pointed cathode tip to be formed. The vertical dimension of the tip depends on the starting material thickness and not on lithography or other nanometer scale process. The width or depth of the cathode can be adjusted to give the proper capacitance and device impedance. A similar set of fabrication steps can be used to form an anode. A natural outcome of the process is a drift region length determined by lithography. A second cavity half would be placed on the top of the wafer to complete the structure. This configuration could be extended to form a portion of a ridge waveguide. In this configuration the resonant frequency could be determined by either a fixed or tunable backshort. Care would be needed to provide a vacuum in the structure. This alternative structure may have fabrication advantages when compared with the vertical structure.

V Summary and Conclusions

This paper has discussed a new THz device, the BT^3, a vacuum based transit time device. This device appears to be able to generate reasonable and useful amounts of power in the THz frequency range. The transit region dimensions and voltages have reasonable values for devices operating between 500 and 1500 GHz. The unanswered question that most effects the device performance is cathode design. However if cathode current densities in the range of 1000 A/cm^2 can be realized, this should prove to be a very useful new device.