THz Range Unipolar Ballistic Tunnel-Emission Transit Time Oscillators

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Abstract

This paper describes THz ballistic transit-time oscillators using a unipolar tunnel injection of electrons from a cathode into a drift region. This new injector design has several advantages over more conventional TUNNETT structures. First, the injection of carriers is by tunneling through a thin barrier, rather than a tunneling p^+n^+ reverse biased junction. The heterobarrier will be easier to fabricate since very high doping and abrupt doping changes will not be required and only n type doping is needed. The p type contact required in a conventional device is not needed, reducing the contact resistance. The barrier current can be tailored to the drift region requirements by proper injector design and the transport in the drift region can be optimized to improve performance. Conventional TUNNETT devices have a high field drift region. The proposed device can have an injector electric field that produces a drift region field similar to a conventional saturated velocity device or a much lower field that will allow ballistic transport. Ballistic transport in the drift region will allow a higher operating frequency.

I. Introduction

Local oscillators are a critical component in all submillimeter and Thz systems. Solid state sources are particularly useful, since they are compact, light, able to withstand vibrations and have modest power requirements. Fundamental solid state oscillators operate to several hundred GHz with harmonic operation further extending the frequency range. However the physics of these devices limits their operation at higher frequencies. Varactor based solid state multipliers can produce nearly a millwatt at frequencies approaching one Thz, but they require a series of complex circuits to reach this frequency. We will describe a new solid state device fundamental oscillator that overcomes some of the physical limitations of existing solid state sources and the complexity of multiplier chains. The next section of the paper will describe some of the limitations of existing solid state oscillators. Section III will describe the operation of the proposed new device. Section IV is a brief summary.

II. Limitations of Existing Solid State Oscillators

Existing solid state sources such as Gunn oscillators and transit time devices operate up to several hundred GHz. However their operation at higher frequencies is limited by device and semiconductor physics. Gunn oscillators require an increase in the effective mass of carriers with increasing electric field. Low electron mass central valley electrons transfer to higher mass satellite valleys when they obtain enough energy from the electric field. The valley transfer is fast because of the larger electron density of states in the upper valley. However the operation also requires a decrease in effective mass as the field is reduced from high values. Problems occur at submillimeter frequencies. The difference in densities of state in the two valleys that favors rapid transfer to the upper valley slows the return to the central valley as the field is reduced. This valley transfer delay limits the fundamental operation of Gunn devices to several hundred GHz.

Transit time devices are limited by device design requirements. A transit time device consists of an injection region to introduce carriers into the structure and a transit region to provide the phase delay needed to produce negative resistance. At frequencies below 100 GHz carriers can be injected by avalanche multiplication. Avalanche multiplication also has the advantage of providing additional time delay that improves the phase angle of the carriers being injected. However the avalanche injector is limited for devices designed for high frequencies. The time delay associated with the avalanche, an advantage at lower frequencies, must be scaled to shorter times.The avalanche region width must also be reduced. Both require higher doping and electric fields in the avalanche region. At frequencies above 100 GHz the fields in the avalanche region become large enough that band to band tunneling can occur. A mixed tunneling and avalanche operation and finally a mainly tunneling operation occurs with increasing frequency. The tunneling injection is very fast but the material structure requirements become very precise at submillimeter frequencies. The goal of the device described in this paper is to overcome the transport limitations associated with the Gunn device and the injector limitations associated with conventional transit time devices to realize a THz frequency solid state oscillator. The design and operation of this new device will be described in the next section.

III. Unipolar Ballistic Transit Time Devices

The structure of the proposed device is shown in Fig. 1. It consists of a cathode and an anode, a heterstructure tunnel barrier and a transit or drift region. Typical materials would be InAs cathode and anode ohmic contacts, an InAlAs barrier and an InGaAs transit region all grown lattice matched on an InP substrate. This structure has several advantages over conventional transit time devices. It has only n type doping, allowing low ohmic contact resistances. The barrier width depends on MBE growth rather than the doping profile of a pn junction. It is much easier to grow a material step than to abruptly change from n to p doping in a junction. The grown barrier width can be less than the depletion layer width associated with even a very heavily doped p^+n^+ junction. The barrier height in a conventional junction depends on the material bandgap. Here the barrier depends on the conduction band offset of the barrier with respect to the cathode. The barrier can be varied by adjusting the barrier material composition, using combinations of InGaAlAs for example.

We can also take advantage of ballistic transport in III-V materials to increase the carrier velocity and the transit time frequency for the same length transit region compared with a conventional device design. This requires careful consideration of the drift region width and voltage drop to obtain the desired overshoot velocities. A small signal model can be used to investigate the operation of ballistic structures. Gilden and Hines [1] published an analytic expression for the small signal admittance of an avalanche transit time device based on a separation of the device into an avalanche injection region and a saturated velocity drift region. This model can be modified to have a tunnel injector and a ballistic drift region. The drift region characteristics will depend on the carrier dynamics of the ballistic carriers and the injection region characteristics will depend on the properties of the tunnel junction.

[1]M. Gilden and M.F. Hines, "Electronic Tuning Effects in the Read Microwave Avalanche Diode, IEEE Trans. On Electron Devices, Volume ED-13, page 169, 1969.

The proposed device exploits ballistic transport in order to produce very short transit times and THz operation. An analytic analysis can be used to predict ideal operation. However we need a more detailed model to better predict realistic device operation. A Monte Carlo transport model based on a two valley constant effective mass approximation has been used to study transient motion in transit regions for different materials. Typical results are shown in Fig. 2 for an applied electric field of 50 KV/cm. The figure shows several characteristics of nearly ballistic transport. For ballistic motion in a constant electric field the acceleration depends inversely on the electron effective mass. The constant acceleration should give a straight line velocity vs. time up to a peak velocity. This is nearly true for the InGaAs with additional energy loss in the InP due to polar optical phonon scattering. We can plot the velocity information vs. distance instead of time. This is shown in Fig. 3. This figure shows the distance dependence of the ballistic motion. The satellite valley energy is smaller in GaAs so electrons in GaAs travel a shorter distance in the constant electric field before obtaining the energy required for valley transfer. InGaAs electrons travel a larger distance with a higher velocity because of the larger valley separation. The net result is that ballistic electrons can have velocities an order of magnitude larger than the saturated velocities in the same material, but only for distances on the order of a fraction a μ and for times of a fraction of a ps.

The properties of the tunneling barrier are also important. The barrier conductance and capacitance are needed for the small signal injector. An analytic expression for the tunnel current through a barrier between 2 metal contacts with the barrier width, height and material properties such as effective mass as parameters is given by Simmons.[2] However our proposed device will have semiconducting rather than metal contacts. Properly accounting for the band bending in the semiconductor contact will give a bias dependent barrier with a conductance superior to a similar barrier with metal contacts. A conduction band diagram for a metal and semiconductor contact barrier is shown in Fig. 4. The unbiased structure on the left has a heavily doped semiconductor or metal contact and an undoped barrier. The conduction band is flat. The center structure is a biased barrier with metal contacts. This is the typical structure described by a Fowler-Nordheim expression for

[2]J. Simmons."Generalized Formula for the Electric Tunnel Effect between Similar Electrodes Separated by a Thin Insulating Film", Journal of Applied Physics, Volume 34, Number 6. pp 1793-1803, June 1963.

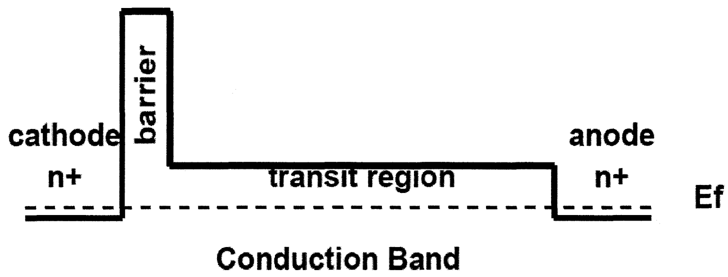

Figure 1: Proposed Unipolar Ballistic Device Structure

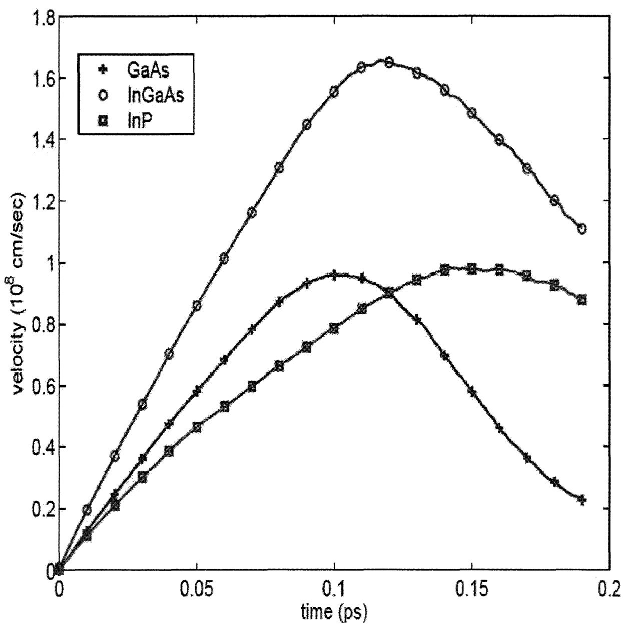

Figure 2: Electron Velocity vs. Time for Various Materials

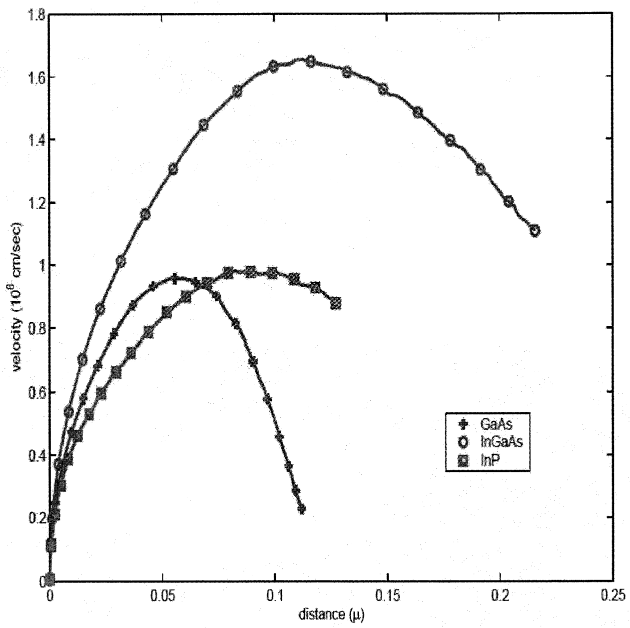

Figure 3: Electron Velocity vs. Distance for Various Materials

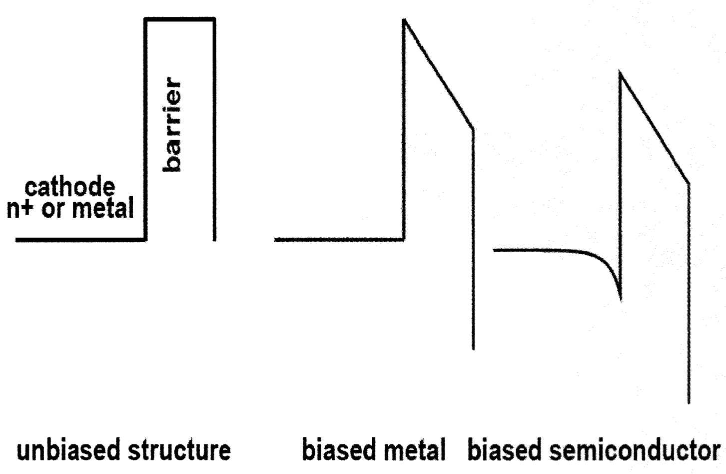

Figure 4: Band Structure for Different Barrier Structures

the tunnel current. All of the applied voltage appears across the barrier. The ballistic structure has the band structure shown on the right. The voltage drop across the barrier is the same as the voltage drop across the center metal structure, but there is additional voltage due to band bending in the semiconductor. The total voltage across the structure is larger for the same barrier voltage drop. However, due to the band bending the "effective barrier height" is lower by the amount of band bending in the semiconductor. The capacitance of the metal contact barrier will be $C_{metal} = \epsilon/w_b$ and will not depend on the bias. The capacitance of the semiconductor contact barrier will be the series combination of the barrier and semiconductor capacitances. The barrier capacitance will be the same as the metal value and the semiconductor capacitance will be the inversion layer capacitance. Except for small differences in the dielectric constants in the barrier and contact materials the electric field will be continuous across the contact barrier interface. A more detailed analysis would include image force lowering at the interface. A simple model based on a Fermi-Dirac solution for the conduction band bending was used with the Fowler-Nordheim current expression for the tunnel current. The barrier height in the tunneling expression will then depend on the semiconductor conditions. This model can be used to investigate the properties of semiconductor barrier structures. The capacitance is on the order of a $\mu F/cm^2$ for a contact doping of $10^{18}/cm^3$. A typical barrier would have an undoped spacer to improve the interface, but this has little effect on the capacitance. If we use an "effective width" for the inversion region based on $C_{inversion} = \epsilon/w_{effective}$, then the inversion layer is 40 to 60 $\AA$ wide. We will see in the next paragraph that the barriers are on the order of 20 to 50 $\AA$ thick, so the effective capacitance of the barrier in the small signal model will be approximately 1/2 the value estimated for the barrier alone.

The next step is to investigate the tunnel current characteristics. The current vs. voltage characteristics of a 30$\AA$ thick, 300 meV high barrier with a $10^{18}/cm^3$ contact doping are shown in Fig. 5. The curves correspond to the characteristics of the barrier alone and the barrier with the band bending and the voltage drop in the contact included. The curves have a change in slope due to the nature of the barrier approximation. The barriers shown in Fig. 4 are approximately rectangular with a constant width with varying voltage and a triangular top portion. When the potential drop across the barrier is equal to the barrier height the conduction band at the right edge will equal the conduction band in the contact on the left side and the barrier will become triangular. Further increasing the voltage across the barrier will reduce the barrier thickness. The inflection point in the current characteristics occurs at the changeover from a rectangular to triangular barrier. The current curves in Fig. 5 show the effect of the semiconductor contact on the tunneling current. The barrier only curve is a conventional Fowler-Nordheim tunnel characteristic. The barrier plus contact curve includes the barrier reduction due to band bending in the contact. The terminal voltage is split between the contact butthe barrier height is reduced by the contact potential drop. The band bending produces nearly a two order of magnitude increase in current density for a given terminal voltage.

The Monte Carlo transport information can be combined with the injector results to obtain initial small signal device predictions. The important parameters in the device design are the voltage drop in the transit region and the injection properties of the unipolar injector. If we assume an InGaAs transit region the carriers can have nearly ballistic transport for voltage drops less than 0.6 volts, a field can be used with each length to give this maximum voltage drop. Five example structures with different drift region lengths are shown in Table I.

length (nm)	Field (KV/cm)	$Frequency(THz)$	Q
80	75	7.4	-12.9
100	60	5.8	-9.6
120	50	4.6	-7.5
140	43	3.8	-6
160	37.5	3.2	-5

Table I Initial Ballistic Structure Results

We would like to operate in the THz frequency range. Devices shorter than 80 nm begin to operate in the range above 10 THz with poor performance due to the susceptance of the structure. The longer devices have a lower operating frequency and better performance, but the electric fields needed to keep the drift region voltage lower than the 0.6 electron volt valley separation become small. The small signal admittance of the five structures were simulated using a constant injector conductance of 1.2e7 $\Omega^{-1}cm^{-2}$ and an injector width of $50\AA$. Other choices of injector conditions will give different results. Fig. 6

shows the small signal admittance for the devices in Table I for frequencies between 2.2 and 8 THz. The markers on the curves are 400 GHz apart. This performance is similar to the behavior of conventional saturated velocity device except the carriers are moving at higher velocities and the frequencies are higher. The peak negative conductance frequency depends on the velocity and the length. This is shown in column 3 of the table for the 5 structures. The device susceptance depends on the operating frequency and the length. Since the optimal negative conductance frequency is $\propto 1/length$ the optimal susceptance is $\propto f^2$. The negative conductance depends on the properties of the induced current waveform. The ballistic device will have an induced current that increases with time or distance through the structure. This triangular waveform will be superior to the constant velocity version with the same injection angle. The negative conductance will have a modest increase with reduced transit region length. The device -Q , the ratio of the susceptance to the conductance is an important parameter for device operation. The power available from the device depends on it's negative resistance, area and the RF voltage along with the parasitic losses. The small signal -Q is a useful measure of the device performance and the device area required to match the device to a given load impedance. These results show that the ballistic structure has the potential for useful operation at THz frequencies.

IV. Summary and Conclusions

This paper described the properties of a new ballistic transit time device with a unipolar tunnel barrier injector. The unipolar injector has both performance and fabrication advantages over conventional p^+n^+ TUNNETT structures. The proposed ballistic transport reduces the transit time compared to a conventional saturated velocity device for the same transit region length and thus increases the operating frequency. However the requirements of ballistic transport limit the device design. Low voltages and electric fields are required for proper operation. The device operation also depends on the unipolar tunnel injector. The results show that the effects of band bending in the semiconductor contact reduce the barrier height under bias and improve the barrier conductance. The small signal results show that these devices can have excellent properties at THz frequencies.

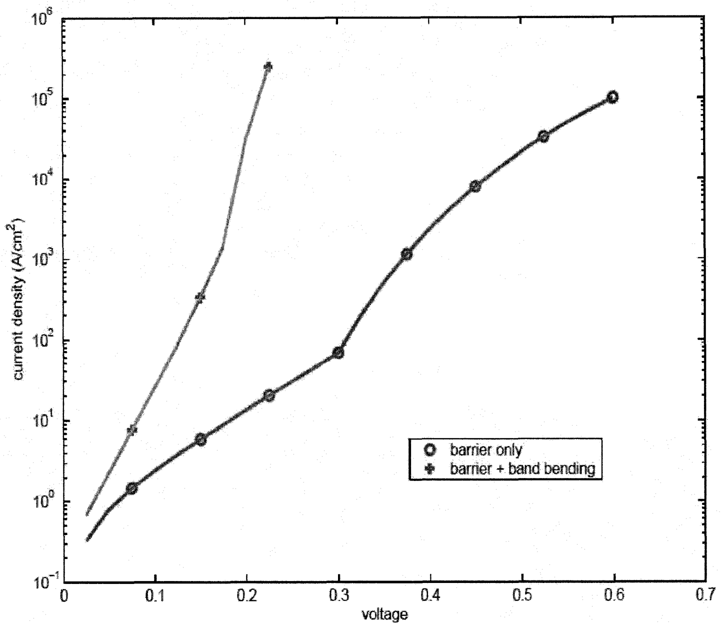

Figure 5: Current vs. Voltage Characteristics for Tunnel Barrier

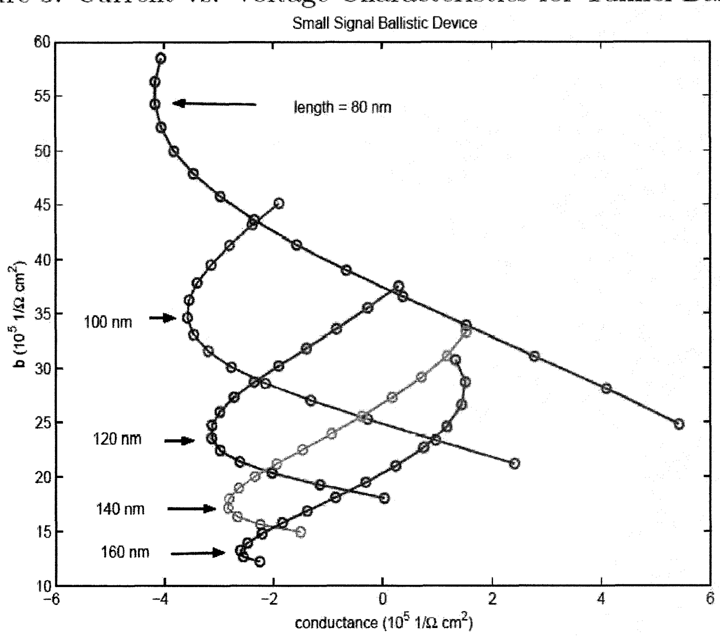

Figure 6: Small Signal Ballistic Operation Between 2.2 and 8 THz

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