A "PLANAR MMIC-COMPATIBLE TRANSFERRED ELECTRON DEVICE"

FOR MILLIMETER-WAVE OPERATION

Final technical report

by

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A planar IC-compatible transferred electron device for millimeter-wave operation

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The objective of this work was to develop a voltage tunable GaAs MESFET oscillator. The active element is a planar field effect controlled transferred electron device (FECTED). Discrete FECTEDs mounted in microstrip circuits produced 20 mW with 5% efficiency (pulsed) and 10 mW with 1% in cw operation. Precise control of frequency and 100% yield was obtained with fully integrated (WMLC) oscillators but only 1% efficiency and 5 mW have been achieved. Higher efficiencies and power levels can be expected with optimized circuitry.
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Abstract

The scope of the work was to optimize device and circuit parameters of planar field effect controlled transferred electron devices ('FE TEDs') to meet the theoretically predicted limits of conversion efficiency (4 - 8 %), bandwidth and upper frequency limit. This was done by employing both computer simulations and empirical methods. The main objective was to develop a voltage tunable 35 GHz MMIC oscillator. The results achieved with both discrete FECTEDs mounted in microstrip circuits and monolithically integrated ('MMIC') oscillators are encouraging: discrete FECTEDs produced pulsed power levels in the 50 mW range with 5% efficiency and 30 mW with 3% efficiency in cw operation. However, variations in FECTED mounting lead to unpredictable bonding wires inductances making it difficult to design an oscillator for a desired frequency. To the contrary, precise control of frequency was possible with fully integrated MMIC oscillators but efficiencies and power levels achieved with these oscillators up to now were only around 1% and 5 - 10 mW, respectively. Besides higher efficiency also better spectral purity was exhibited by discrete devices due to the dielectric resonator used in the microstrip circuit. It is almost certain that MMIC oscillator efficiency can further be increased by improving coupling circuitry. It should be emphasized that, due to our well controlled technology, very high yield (100% for the third batch fabricated in July 1989) with equal DC and AC parameters within one batch of MMIC oscillators has been achieved which is primarily a consequence of the simplicity of the device.

List of Keywords

MMIC compatible transferred electron devices ('FE TEDs')
Fully monolithically integrated ('MMIC') oscillators
Voltage tunable signal source at millimeter wave frequencies (26 - 40 GHz)
Gallium Arsenide and Indium Phosphide devices
Injection controlled planar Cunn diodes
Gunn-effect
Program Objectives

The aim of this program was to optimize device and circuit parameters of both discrete and monolithically integrated planar field effect controlled transferred electron devices ("FECTEDs") to meet the theoretically predicted limits of conversion efficiency, bandwidths and upper frequency limit. The research program was to be directed at problems associated with device physics, device technology and circuit design.

Work performed on this program

The work on this program can be divided into three areas - device simulations, fabricating and mounting discrete FECTEDs in properly designed microstrip circuits and fabricating monolithically integrated FECTEDs ("MMIC oscillators"). Details on the first two areas have been presented in six interim reports as well as in papers published during the course of this program. They will be reviewed briefly in this (final) report. The bulk of this report will be devoted to the voltage tunable MMIC oscillator which was the final goal to be achieved in this program.

Device structure

A cross sectional view of the FECTED is shown in Fig. 1. It is basically a planar transferred electron device with a MESFET-like cathode contact. The electron injection is controlled by the negatively biased Schottky gate to the extent that travelling domains cannot form. Instead, a stationary high field domain forms in the gate-drain region which exhibits a frequency-independent negative differential resistance. This two-terminal negative resistance is used for both amplifying and generating signals at frequencies determined by external circuitry.

Device simulations

Computer simulations have been performed in order to find optimum values for doping level, device geometry, drain bias voltages and RF voltage swing. Since only a one-dimensional computer program was available the
two-dimensional MESFET-like cathode structure could not be included in the computations. It was therefore simulated by a constant current injector. In a real device, the magnitude of the injected current can be adjusted by the negative gate bias voltage. Of course, the optimum gate length cannot be obtained with this computer program and has been determined empirically. In this work gate lengths between 0.5 μm and 2 μm have been used. A short gate might be advantageous as a small DC voltage drop is obtained thereby maximizing efficiency. On the other hand, a MESFET cathode with a very short gate (smaller than 0.1 μm) will not allow constant current injection. A gate length of 0.7 μm might be a good compromise.

The simulations have shown, that best efficiencies (4 % - 8 %) can be obtained with devices having doping levels in the vicinity of $5 \times 10^{16}$ cm$^{-3}$ and gate-drain spacings between 2 and 5 μm /3/.

Discrete FECTED oscillators

Discrete FECTEDs made from both GaAs- and InP-materials have been tested in microstrip circuits shown in Fig. 2. The three contacts - source, gate and drain are wire-bonded to 50 microstrip lines. Microwave signals are coupled to and from the drain contact. Two identical stub-terminated 3/8 long sections, connected to gate and source, provide capacitive loads to them thereby compensating for bonding wire inductances. Amplification over almost 10 GHz has been measured with a maximum gain at 37 GHz. In order to produce free running oscillations a dielectric resonator was placed near the drain contact. The results obtained are summarized in the table shown below.

<table>
<thead>
<tr>
<th>Material</th>
<th>Drain Bias</th>
<th>Pulse</th>
<th>$V_{DS}$ (V)</th>
<th>$V_{GS}$ (V)</th>
<th>$I_{D}$ (A)</th>
<th>eff. %</th>
<th>P(mW)</th>
<th>F(GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>1 μs</td>
<td>7.0</td>
<td>-3.0</td>
<td>0.15</td>
<td>5.3</td>
<td>56</td>
<td>28.4</td>
<td></td>
</tr>
<tr>
<td>GaAs</td>
<td>1 μs</td>
<td>6.1</td>
<td>-7.9</td>
<td>0.13</td>
<td>4.9</td>
<td>39</td>
<td>37.3</td>
<td></td>
</tr>
<tr>
<td>InP</td>
<td>1 μs</td>
<td>11.3</td>
<td>-4.3</td>
<td>0.17</td>
<td>2.9</td>
<td>33</td>
<td>34.4</td>
<td></td>
</tr>
<tr>
<td>GaAs</td>
<td>60 μs</td>
<td>6.7</td>
<td>-8.35</td>
<td>0.15</td>
<td>2.9</td>
<td>29.3</td>
<td>29.8</td>
<td></td>
</tr>
<tr>
<td>GaAs</td>
<td>60 μs</td>
<td>3.4</td>
<td>-9.1</td>
<td>0.144</td>
<td>3.8</td>
<td>29.8</td>
<td>37.3</td>
<td></td>
</tr>
</tbody>
</table>
Monolithic FECTED oscillators

Among all the well known advantages of integration of both active and passive elements on a single semi-insulating substrate (MMIC) the salient feature is the elimination of bond wires which are a source of uncontrolled parasitic elements making precise control of oscillation frequency impossible.

Fig. 3 shows a photograph of the 5 x 5 mm² monolithic oscillator chip. The circuit connected to the FECTED is similar to the microstrip circuit shown in Fig. 2 except for an additional Y-shaped resonator section replacing the dielectric resonator used in the hybrid circuit. The length of the upper bars of the "Y" has been chosen to provide an inductive impedance to the drain contact. This inductance determines the frequency of oscillation in conjunction with the device capacitance. This, of course, is valid only if the two other (mushroom-like) resonating elements provide ground potential to both gate and source contacts at the oscillation frequency. The length of these two stub-terminated transmission lines has been chosen /2 at 35 GHz.

Monolithically integrated FECTEDs have produced stable oscillations in a frequency band around 35 GHz. The results are summarized in the table shown below.

<table>
<thead>
<tr>
<th>Device No.</th>
<th>Vds(V)</th>
<th>Vgs(V)</th>
<th>I(A)</th>
<th>eff. %</th>
<th>P(mW)</th>
<th>f(GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>-6</td>
<td>0.073</td>
<td>0.95</td>
<td>5.7</td>
<td>36.1</td>
</tr>
<tr>
<td>2</td>
<td>7.5</td>
<td>-6.7</td>
<td>0.07</td>
<td>1.08</td>
<td>5.7</td>
<td>35.7</td>
</tr>
<tr>
<td>3</td>
<td>6.8</td>
<td>-4.8</td>
<td>0.08</td>
<td>1.03</td>
<td>5.6</td>
<td>35.8</td>
</tr>
</tbody>
</table>

The three devices (No. 1, 2 and 3) exhibit very similar electrical parameters. 100 % yield has been obtained with this batch of devices confirming that improved reliability can indeed be obtained with the MMIC approach. Another advantage of the MMIC version is the wide tuning range achieved with gate bias tuning: 1 GHz with 3 db output power variation and 500 MHz with 1 db variation. Fig 4 shows spectral characteristics measured at three different frequencies. As expected from classical oscillator theory the os-
oscillator noise decreases with increasing frequency. However, a comparison with the spectral characteristics of discrete dielectric resonator loaded FECTED oscillators shows that the MMIC oscillator produces higher noise levels than discrete oscillators /2/ which is obviously due to the low quality factor of the MMIC oscillator.

Conclusions

Our conclusions based on this contract are as follows:

i Planar GaAs and nP field effect controlled transferred electron devices ('PECTEDs') are attractive candidates for fabricating monolithically integrated millimeter-wave oscillators due to their simple structure and the absence of transit-time effects.

ii Discrete FECTEDs mounted in duroid based microstrip circuits have produced the theoretically predicted efficiencies (5%) at ka-band frequencies with power levels around 50 mW. At 29 GHz and 34 GHz the highest output power levels ever obtained with lateral TEDs and FET oscillators and at 37 GHz the highest lateral TED output power have been produced. Optimum values for active layer doping and thickness are $5 \times 10^{16}$ cm$^{-3}$ and 0.9 μm, respectively.

iii Monolithically integrated FECTED-oscillators ('MMIC' oscillators) have been fabricated with high yield, high reliability and precise frequency control which is primarily a consequence of eliminating bonding wires. With unoptimized circuits 1% efficiency and 5 mW output power have already been obtained in cw-operation. With better coupling circuitry higher values (perhaps 3% eff. and 15 - 30 mW) should easily be obtainable.

iv Discrete FECTEDs mounted in microstrip circuits loaded with a dielectric resonator exhibit better spectral characteristics than MMIC FECTEDs due to the high quality-factor of dielectric resonators, which cannot be used in monolithic circuits because of their large size. To reduce MMIC oscillator noise one must provide other resonating elements such as overlay or inter-digitated capacitors, etc. Further work along these lines is clearly necessary. However, since FECTEDs are two-terminal devices,
circuit design is probably much easier than it is in the case of three-terminal devices as transistors are. In order to further improve efficiency we recommend to use modulation doping, i.e., a HEMT structure which should exhibit a higher peak to valley ratio due to the high low field mobility and to real space transfer at high fields. The use of such a structure would make the FBCTED HEMT-compatible.

List of participating personnel

Dr. Kurt Lubke
Dr. Helmut Scheiber
Dipl.-Ing. Christian Diskus
Gerald Hofmann
Johann Katzenmayer
Gabriele Roitmayr
List of publications


List of talks


also presented at the European Workshop on Compound Semiconductor Integrated Circuits, May 9. - 11., 1988, Lugano, Switzerland


also presented at the European Workshop on Compound Semiconductor Integrated Circuits, May 10. - 12., 1989, Cabourg, France

List of illustrations

Fig. 1 Cross sectional view of the FECTED
Fig. 2 Microstrip circuit configuration of a 37 GHz FECTED
Fig. 3 Photograph of a MMIC FECTED oscillator
Fig. 4 Spectral characteristics of a MMIC FECTED oscillator
Fig. 1: Cross sectional view of the FECTED

Fig. 2: Microstrip circuit configuration of a 37GHz FECTED
Fig. 1 Photograph of a MMIC FECTED oscillator
Fig. 1 - Spectral characterization of a MMIC oscillator
DEVICE STRUCTURE

Fig. 1 shows a cross-sectional view of the NiZn ferrite field-controlled pentode, showing the reverse biasing of the pentode type 1. A reverse bias of about 10 V is applied to the grid to prevent simple types of oscillation which may otherwise occur at higher input levels and are easier in manufacture at lower input levels. In place of the reverse bias, a variable resistor may be used as in Fig. 2. The use of this resistor is to correct the abnormal behavior of the amplifier, a feature common to all types of ferrite devices. For the present invention, this means that in a normal operation, the input levels are adjusted from 5 to 40 V. The power level required is between 10 and 80 mW. The advantage of the NiZn ferrite field-controlled pentode (F-C-P) is that the reaction current is maintained continuously by the reverse bias.
transmission lines providing capacitive reactances to both source and gate contacts. They constrain the various bonding wire inductances at upper Rambolt frequencies with a resistance at 12 GHz thereby producing a maximum reflection gain at that frequency. Amplification of about 10 dB has been measured with a GaAs FET/CID mounted in this circuit as is shown in Fig. 3. A negative gate bias voltage of about -8 V was applied to the device.

Fig. 3 Output and input power versus frequency of a FET/CID reflection test amplifier.

In order to produce free running oscillations, a dielectric resonator was to be clamped near the device input. The first oscillation results have been summarized in the table shown below. These data have been measured using Hittite VHF-voltage references in order to avoid possible burnout.

<table>
<thead>
<tr>
<th>Device</th>
<th>VHF Voltage</th>
<th>Au-C</th>
<th>Au-A</th>
<th>Au-C</th>
<th>Au-A</th>
<th>Au-C</th>
<th>Au-A</th>
<th>Au-C</th>
<th>Au-A</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>5.0 V</td>
<td>5.5 V</td>
<td>5.6 V</td>
<td>5.5 V</td>
<td>5.6 V</td>
<td>5.5 V</td>
<td>5.6 V</td>
<td>5.5 V</td>
<td>5.6 V</td>
</tr>
<tr>
<td>GaAs</td>
<td>6.0 V</td>
<td>6.5 V</td>
<td>6.6 V</td>
<td>6.5 V</td>
<td>6.6 V</td>
<td>6.5 V</td>
<td>6.6 V</td>
<td>6.5 V</td>
<td>6.6 V</td>
</tr>
<tr>
<td>GaAs</td>
<td>7.0 V</td>
<td>7.5 V</td>
<td>7.6 V</td>
<td>7.5 V</td>
<td>7.6 V</td>
<td>7.5 V</td>
<td>7.6 V</td>
<td>7.5 V</td>
<td>7.6 V</td>
</tr>
</tbody>
</table>

Figs. 4 shows the spectral characteristic of a free running 8 MHz over-sampled FET/CID oscillator.

Fig. 4 Spectrum of an 8 MHz FET/CID oscillator.
IC-COMPATIBLE 48mW Ka-BAND GaAs TRANSFERRED-ELECTRON OSCILLATOR

Indexing terms: Semiconductor devices and materials, Field-effect devices, Oscillators, Microwave oscillators, Planar transferred-electron oscillators, monowave generation.

The performance of a planar field-effect controlled transferred-electron oscillator has been significantly improved by reducing the length of the low field region near drain and source. 15mW with 7% efficiency at 28.4GHz and 24mW with 12% at 37.4GHz have been obtained, which is a factor of 6.5 times larger than was obtained a year ago.

It is well known that GaAs monolithic MESFET amplifiers can be operated at millimetre-wave frequencies with high output power levels and high efficiencies.1 The internal development of meso FETs also resulted in high performance oscillators producing 30mW at 34GHz with 30% efficiency and in a 115GHz monolithic GaAs FET oscillator2 which, however, produced a drastically reduced output power of only 0.1mW. The steep decrease of power cannot be explained solely by the 1/2 law due to the transit-time limitation. FETs are subject to other effects such as short channel effects,1 current injection into the buffer layer or parasitic bipolar effects1 must be made responsible in addition to the difficulty of circuit matching of a three terminal device.

A simpler approach to monolithic oscillator design is to use a planar transferred-electron oscillator (TEO) with an injection limiting cathode contact as first described in 1982. In this device the electron injection is controlled by a negatively biased Schottky gate preventing travelling domains from forming. Instead, a stationary high field domain forms in the gate-drain region which exhibits a frequency independent negative resistance. The device is thus not subject to the usual transit-time limitation that conventional FETs and FETs are suffering from.

![Fig 1 Cross-sectional view of FECTED](image)

The purpose of this letter is to report new results obtained with devices having reduced parasitic resistances. Fig. 1 shows a cross-sectional view of the device used. It consists of a 0.9µm thick GaAs grown active layer (Wn = 0.5 × 10^{20} cm^{-3}) La Schottky drain contact, an ohmic source contact and a 25µm long overlapping Schottky gate separated from the source by a 500nm thick GaAs layer which connects the gate to source AC-wise. The new feature of the device is that both source and drain contacts have been moved towards the gate making the depths of the low field regions outside the stationary high field domain much shorter than those in previously used devices.2 This results in significantly smaller series resistances. The new device has been tested in microstrip circuits identical to those used in previously performed experiments.1,3 It shows the configuration of the test circuit. There are two identical resonators connected to source and gate, respectively. These are sub terminated (4 x 4) and 20dB transmitters giving adequate impedance in order to compensate for the various loading in circuits. In addition to these a dielectric resonator (f = 46GHz) is placed near the device for establishing stable oscillations. Without this resonator the device exhibits stable reflection gain of several dB from 10 to 40GHz with a 10dB gain peak at 14GHz.

Two modes of operation have been observed depending on the magnitude of the gate bias voltage. At Vg = 5V and Vd = 6V transit-time oscillations occur characterized by cyclic domain formation at the gate and domain extinction at the drain contact. In this mode 45mW pulsed output power has been generated with 4.3% efficiency at 28.4GHz. At 15mV the same device oscillated in the so-called4 so-called B field-effect controlled transferred electron device or TETO mode characterized by a "breathing" high field domain located underneath the gate and extending somewhat into the gate-drain region. This mode has also been called TET mode by Rolland et al.5 It is a transit-time independent mode of operation and therefore circuit dominated 24mW with 3.2% efficiency have been obtained at 37.4GHz, which is 4GHz above the transit time frequency.

![Fig 2 Measuring scheme of TETO oscillator](image)

To avoid possible burn-out the devices exhibiting the best data have been operated only with pulses up to 10ms. Lower doped devices with 10% lower drain currents have been operated CW producing 19mW with 2.5% efficiency at 28.4GHz and 11mW with 21% efficiency at 37.4GHz.

In summary we have demonstrated that planar GaAs FECTED oscillators are attractive MMIC compatible candidates for local oscillator applications at Ka-band and possibly at higher frequencies as they are not transit-time limited compared to conventional FETs and FETs and at 28.4GHz the highest output power ever obtained with lateral FETS4 and at 28.4GHz the highest output power ever obtained with lateral TETO4 and FET oscillators have been achieved.

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References

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MIMIC-Compatible GaAs and InP Field Effect Controlled Transferred Electron (FECTED) Oscillators

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AND HARTWIG W. THIM, SENIOR MEMBER, IEEE

Abstract—An MIMIC-compatible transferred electron oscillator is described which utilizes the frequency-independent negative resistance of the stationary charge depletion zone formed in the channel of a MESFET. Devices fabricated from GaAs and InP exhibit 50 mW at 20 GHz and 55 mW at 34 GHz, respectively. CW power levels are somewhat lower (30 mW). These power levels are the highest ever obtained with lateral transferred electron oscillators and FET oscillators.

I. INTRODUCTION

CONTINUOUS progress during the last few years in the development of millimeter-wave circuits for communication and radar systems has stimulated the search for a planar IC-compatible millimeter-wave source for both local oscillator and VCO applications. The two successfully applied approaches are the GaAs FET oscillator and the planar transferred electron oscillator (TEO).

The intense developments of millimeter-wave FETs have resulted in high-performance oscillators capable of producing 30 mW at 14 GHz with 50 percent efficiency [1] and in a 115 GHz monolithic GaAs FET oscillator [2], which, however, produces a drastically reduced output power of only 0.1 mW. This steep decrease of power cannot be explained merely by the inverse square law due to the transit time limitation that FETs are subject to. Other effects, such as short-channel effects [3], current injection into the buffer layer, or parasitic bipolar effects [4], must be considered in addition to the difficulty of circuit matching in a three-terminal device. FETs exhibit lower efficiencies but require simpler biasing circuits since they are two-terminal devices. They are much easier to manufacture because submicrometer dimensions are not needed. In addition, TEOs are known for their superior noise performance. However, conventional TEOs are usually operated in the traveling domain mode ("Gunn oscillations") [5] they also suffer from the transit time (1/f^2) limitation, leading to a 6 dB per octave decrease of output power.

A method for circumventing the transit time limitation is to use a planar TEO with an injection limiting cathode contact of the type first described in 1982 [6]. In this device the electron injection is controlled by a negatively biased Schottky gate to the extent that traveling domains cannot form. Instead, a stationary high-field domain forms in the gate-drain region which exhibits a frequency-independent negative resistance. The injection current of the device can be continuously adjusted by the Schottky gate bias voltage, allowing some additional tuning. Computer simulations described in this paper explain the principal operation of the device and show the dependence of power and efficiency on doping level, device length, and operating frequency. Maximum efficiencies obtainable with GaAs devices are of the order of 9 percent at frequencies between 30 and 50 GHz. Experimental efficiencies measured between 30 and 37 GHz are somewhat lower (5 percent) but confirm the absence of the transit time limitation at Ka-band frequencies.

II. DEVICE STRUCTURE

A cross-sectional view of a typical device is shown in Fig. 1. It is similar to a normal MESFET having an extended gate-drain region and an integrated gate-source capacitance. MOVCD-deposited n-type GaAs and InP layers have been used. The InP n-layer is covered with a thin (100 Å) undoped layer in order to obtain a good Schottky barrier. The active layer doping concentrations have been chosen between 2 \times 10^{18} \text{ cm}^{-3} and 5 \times 10^{19} \text{ cm}^{-3} for GaAs and 5 \times 10^{18} \text{ cm}^{-3} for InP. All devices consist of an ohmic source contact (Ni-Au Ge), a Schottky anode contact (Ti, Au), and an overlapping Schottky gate contact separated from the source by a 5000 Å thick chemical vapor deposited SiO_2 layer. The device width is 400 \text{ Å}. Both the length of the Schottky gate and the distance between gate and source have been chosen to be 0.5 \text{ μm}. The length of the active region between gate and anode contact was varied from 2.3 to 5 \text{ μm}. The thickness of the semisolating substrate is 100 Å.
III. DEVICE ANALYSIS AND SIMULATION

It is well known that in a normal MESFET a stationary high-field domain forms in the gate-drain region. The formation of traveling Gunn domains is prevented when the electron injection through the gate is reduced to about 50 percent of the peak current level [7]. Under this condition, a negative differential resistance occurs in the gate-drain region due to the transferred electron ("Gunn") effect.

For better understanding of the whole process, a one-dimensional computer simulation has been performed by solving Poisson's equation, the continuity equation, and the integral current relation. The electron velocity \( v(E) \) is calculated using the analytical expression [8]:

\[
v(E) = \frac{\mu E + v_s (E/E_s)^4}{1 + (E/E_s)^4},
\]

where \( \mu \) is the field-dependent mobility, \( v_s \) is the saturation velocity, and \( E_s \) is the field at which the electron velocity reaches its maximum.

According to this equation the velocity is an instantaneous function of local field, thus neglecting delays caused by intervalley scattering and energy relaxation. Hence the results of this analysis are valid only for frequencies up to approximately 60 GHz and for device lengths greater than 1 \( \mu m \). The structure used in the simulation is shown in Fig. 2. The injection limiting cathode contact represents the one-dimensional equivalent of the gate-source region of a real device. The current \( I_j \) injected into the first (left) cell of the device was kept constant in order to properly simulate the saturation current of a MESFET. One-dimensional doping fluctuations as well as a higher doping region at the cathode contact have also been incorporated, as they are known to act as nucleation centers for dipole domains in devices with an overcritical \( N_D L \) product. The simulation parameters are summarized in Table I.

Table I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average doping level</td>
<td>( 10^{15} - 5 \times 10^{16} ) cm(^{-3} )</td>
</tr>
<tr>
<td>Device length</td>
<td>2.5 ( \mu m ), 5 ( \mu m ), 10 ( \mu m )</td>
</tr>
<tr>
<td>DC voltage</td>
<td>4.5 V, 20 V</td>
</tr>
<tr>
<td>Amplitude of AC voltage</td>
<td>4.5 V - 18 V</td>
</tr>
<tr>
<td>Frequency</td>
<td>25 GHz - 60 GHz</td>
</tr>
</tbody>
</table>

Fig. 3 shows a sequence of field and carrier distributions of a 5-\( \mu m \)-long device calculated at different instants of time and the accompanying voltage and current waveforms. The frequency of operation is 35 GHz, and the dc voltage is 4.5 V; the amplitude of the ac voltage is 3.5 V, allowing a voltage swing down to threshold. As can be seen from Fig. 3 the field is below threshold in a substantial part of the device. This region acts as a positive resistance, thereby contributing to loss. It also causes an upper frequency limit (AC limitation). In order to minimize the influence of this lossy region the device length must be kept short.

Fig. 3 also shows that bunches of electrons traverse the depletion region, thereby introducing transit time effects. These effects can enhance efficiency if both the doping level and the bias voltage are chosen properly. Fig. 4 shows calculated efficiencies versus frequency for different doping levels and bias voltages. Higher efficiencies occur at higher frequencies at higher doping levels and lower bias voltages, which can be attributed to adjusting the transit time of the electron bunch close to the oscillation period.

The best calculated efficiencies in the 30-60 GHz range are about 9 percent for GaAs devices and are somewhat higher for InP devices when allowing a current injection of about 58 percent of the peak current. For slightly increased injection current levels the device breaks into traveling domain (Gunn) oscillations at the gate-drain transit time frequency.
Figure 1 - (a) Calculated carrier concentration vs. field distribution (Continued)
IV. EXPERIMENTAL RESULTS

Both GaAs and InP devices have been tested in microstrip circuits fabricated on 250-μm-thick Duroid substrate, as shown in Fig. 3. The device is glued onto the copper heat sink within a rectangular hole cut into the Duroid substrate. All three contacts—source, gate, and drain—have been connected to the microstrip circuit using gold bonding wires. The two identical stub-terminated 3A/8 long transmission lines provide capacitive impedances to both source and gate, compensating bonding wire inductances. With this circuit amplification over almost 10 GHz has been measured with a maximum gain at 37 GHz. A drain voltage of 7.5 V and a negative gate
voltage of a GaAs device at 28.4 GHz for short pulse operation was 5.3 percent. At 37 GHz the efficiency is only half that obtained with long pulses. A small decrease of efficiency is observed, which is attributed to such parasitic impedances as the drain-gate capacitance.

The efficiencies obtained with InP devices are somewhat smaller owing to the difficulty of making a good Schottky gate contact to InP. Nevertheless, the output power levels of InP devices are in the 50 mW range.

In order to prevent burnout, the higher-current devices also have been tested with long drain pulses. The output power levels obtained with long pulses are generally lower due to the high operating device temperature. This temperature level is believed to be close to that occurring in CW-operated GaAs devices where the power output remains unchanged when increasing the duty cycle from 30 to 90 percent.

Fig. 7 shows the spectral characteristics of a free-running 8 mW CW-operated FECTED oscillator. A careful inspection of this characteristic one can speculate that FECTED oscillator noise is comparable to conventional Gunn oscillator noise.

V. CONCLUSIONS

It has been shown that GaAs or InP FECTED oscillators are attractive candidates for monolithic millimeter-wave integrated circuits, especially for very high frequencies since they are not subject to transit time limitations, as conventional FET or Gunn oscillators at 29 GHz and 34 GHz the highest output power levels ever obtained with lateral FEO's and Gunn oscillators and at 37 GHz the highest lateral FEO output power have been produced. A further increase of output power should be possible by simply increasing the device width, as this is not a critical dimension with respect to gate resistance. However, the efficiencies measured at 37 and 45 GHz are significantly lower than those obtained with GaAs devices at these frequencies due to the absence of the transit time limitation and the smaller loading capacitance required by the two-terminal FECTED. However, intervals between transition times will increase and energy relaxation times reduce the effective peak-to-valley ratio at high frequencies causing an upper frequency limit that FET oscillators are not subject to. This frequency limit has not yet been determined.

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