A PLANAR MMIC-COMPATIBLE TRANSFERRED ELECTRON DEVICE FOR MILLIMETER-WAVE OPERATION

Final technical report

by

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February 1990

R&D 5302-EE-01

United States Army
EUROPEAN RESEARCH OFFICE OF THE U.S. ARMY
London, England

CONTRACT NUMBER: DAJA 45-86-C-0039
Prof. Dr. Hartwig Thim

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 7th (final) report	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A planar IC-compatible transferred electron device for millimeter-wave operation		5. TYPE OF REPORT & PERIOD COVERED Final report Sep. 86 - Sep. 89
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Hartwig W. Thim		8. CONTRACT OR GRANT NUMBER(s) DAJA 45-86-C-0039
9. PERFORMING ORGANIZATION NAME AND ADDRESS Microelectronics Institute University of Linz Altenbergerstr. 69, A-4040 Linz, Austria		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Contracting Office (Mr. G. B. Evans) 447th Area Support Group P.O.Box 160, Warrington, Cheshire, England		12. REPORT DATE February 16, 1990
		13. NUMBER OF PAGES 13
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) USARDS Group UK 223 Old Marylebone Road London NW1 5TH		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

The view, opinions, and/or findings contained in this report are those of the author and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

MMIC-compatible transferred electron devices,
field effect controlled TEDs (FECTEDs),
VCO at millimeter-wave frequencies (26 - 40 GHz)
Gallium Arsenide and Indium Phosphide
transferred electron (Gunn) effect

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective of this work was to develope a voltage tunable 35 GHz MMIC oscillator. The active element is a planar field effect controlled transferred electron device ("FECTED"). Discrete FECTEDs mounted in microstrip circuits produced 50 mW with 5 % efficiency (pulsed) and 30 mW with 3 % in cw operation. Precise control of frequency and 100 % yield was obtained with fully integrated ("MMIC") 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 ("FECTEDs") 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 ("FECTEDs")
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 Gunn 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 /1/, /2/. 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.

Material	Drain Bias Pulse Width	V_{DS}(V)	V_{GS}(V)	I(A)	eff. %	P(mW)	f(GHz)
GaAs	1 µs	7.0	-5.0	0.15	5.3	56	28.4
GaAs	1 µs	6.1	-7.9	0.13	4.9	39	37.4
InP	1 µs	11.3	-4.3	0.17	2.9	55	34.4
GaAs	60 µs	6.7	-8.35	0.15	2.9	29.5	29.8
GaAs	60 µs	5.4	-9.1	0.144	3.8	29.8	37.3

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 mm^2 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.

Device No.	V_{DS}(V)	V_{GS}(V)	I(A)	eff. %	P(mW)	f(GHz)
1	8	-6	0.075	0.95	5.7	36.1
2	7.5	-6.7	0.07	1.08	5.7	35.7
3	6.8	-4.8	0.08	1.03	5.6	34.8

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 oscillator noise decreases with increasing frequency. However, a comparison with the spectral characterisitics 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 InP field effect controlled transferred electron devices ("FECTEDs") 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 TEO's and FET oscillators and at 37 GHz the highest lateral TEO 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 elementes 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 FECTED HEMT-compatible.

List of participating personnel

Dr. Kurt Lübke
Dr. Helmut Scheiber
Dipl.-Ing. Christian Diskus
Gerald Hofmann
Johann Katzenmayer
Gabriele Roitmayr

List of publications

/1/ H. Scheiber, K. Lubke, C. Diskus and H. Thim, "An IC-compatible 45 mW ka-band GaAs TEO", 1988, Electronic Letters, vol. 25, pp. 223-224

/2/ K. Lubke, H. Scheiber, D. Grutzmacher, C. Diskus and H. Thim, "MMIC-compatible 55 mW InP and GaAs 30 - 40 GHz field controlled TE oscillators", 1989, IEEE MTT-S Digest, pp. 729-730

/3/ H. Scheiber, K. Lubke, D. Grutzmacher, C. Diskus and H. Thim, "MMIC-compatible GaAs and InP field effect controlled transferred electron (FECTED) oscillators", 1989, IEEE Transactions on MTT, vol. 37, No. 12, pp. 2093-2098

List of talks

H. Scheiber, K. Lubke, C. Diskus and H. Thim, "A planar 10 mW 30 GHz MIC-compatible GaAs MESFET-like oscillator", 14th International Symposium on Gallium Arsenide and Related Compounds, September 28. - 30., 1987, Capsis Beach, Crete

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

K. Lubke, H. Scheiber, D. Grutzmacher, C. Diskus and H. Thim, "MMIC-compatible 55 mW InP and GaAs 30 - 40 GHz field controlled TE oscillators", IEEE International Microwave Symposium, June 12. - 16., 1989, Long Beach, California

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

List of illustrations

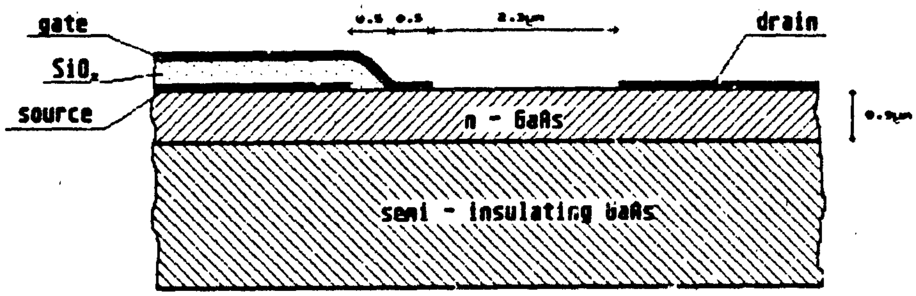

Fig.1: Cross sectional view of the FECTED

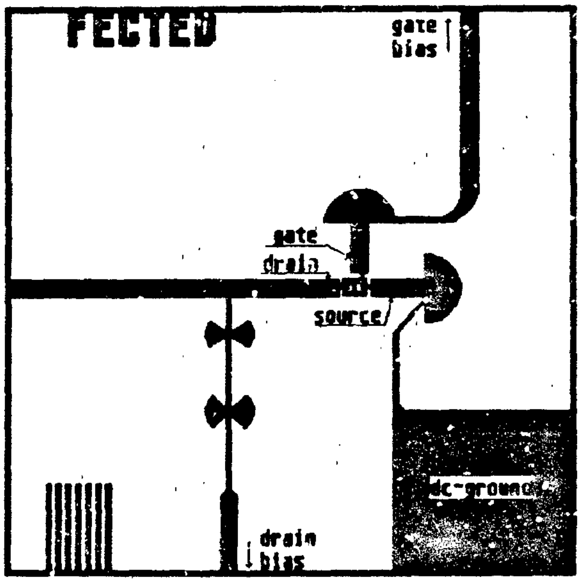

Fig.2: Microstrip circuit configuration of a 37GHz FECTED

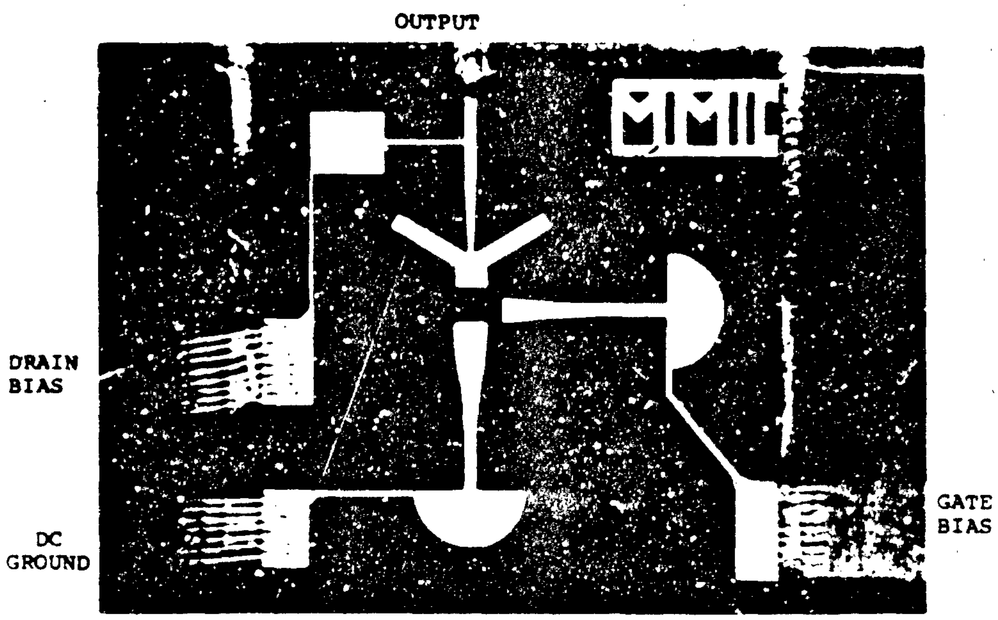

Fig.3 Photograph of a MMIC FECTED oscillator

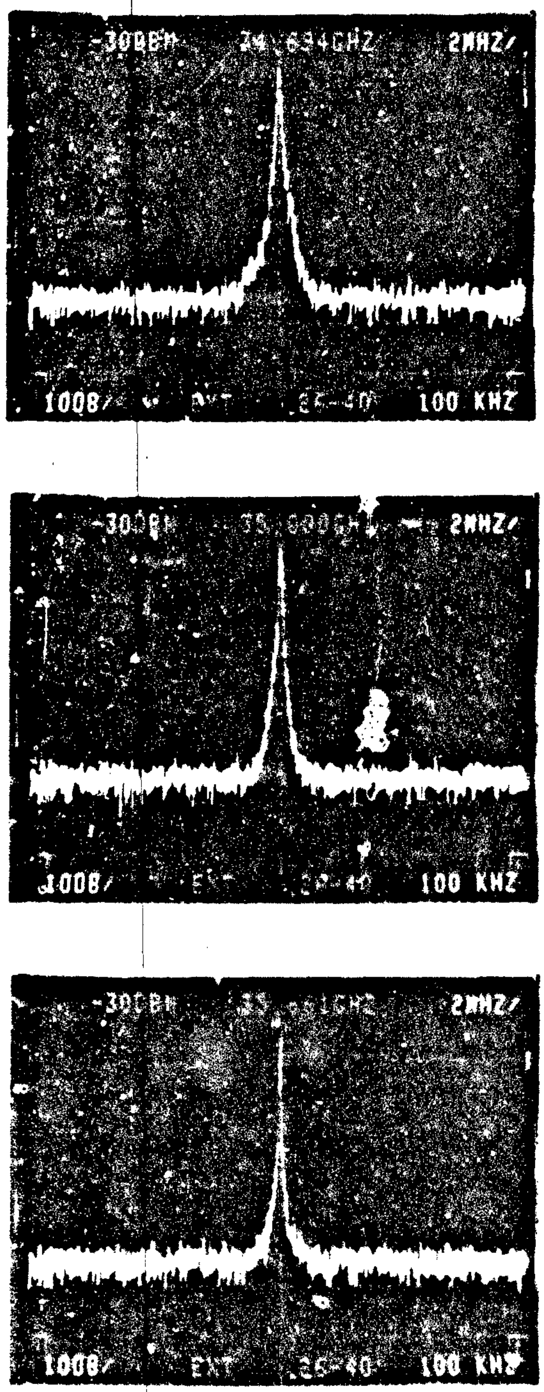

Fig. 4 Spectral characteristics of a MMIC oscillator

MMIC-COMPATIBLE 55 mW InP AND GaAs 30 - 40 GHz FIELD CONTROLLED TE-OSCILLATORS

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ABSTRACT

55 mW 34 GHz InP, 46 mW 29 GHz GaAs and 39 mW 37 GHz GaAs lateral MMIC-compatible transferred electron oscillators with MESFET injection contacts have been fabricated exhibiting 2.4%, 5.1% and 4.3% efficiencies, respectively. CW power levels are somewhat lower (30 mW). The achieved power levels are the highest ever obtained with lateral TEOs and FET-oscillators.

INTRODUCTION

Continuous progress in the development of millimeter wave monolithic integrated receivers has stimulated the search for a planar source for local oscillator applications. The two successfully applied approaches are the GaAs FET oscillator /1/ /2/ /3/ and planar transferred electron oscillators /4/ /5/. FET oscillators are high efficiency devices (30% at 35 GHz) but suffer from transit-time effects (1/f limitation) and circuit matching difficulties. Transferred electron oscillators exhibit lower efficiencies but require simpler loading circuits as they are two-terminal devices and are easier to manufacture as submicrometer dimensions are not needed. TEOs are also known for their superior noise performance.

The purpose of this paper is to report new results obtained with planar InP and GaAs transferred electron oscillators having a MESFET cathode contact. In this device the electron injection is controlled by a negatively biased Schottky gate preventing travelling domains (Gunn oscillations) 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 (1/f) limitation conventional TEOs and FETs are suffering from. This makes this kind of device particularly well suited for the 30 - 100 GHz range. So far the fabricated devices have been tested only up to 40 GHz. The power levels obtained are higher than those produced by GaAs-FET oscillators /1/ and those obtained with "notched" InP TEOs /4/. The advantage of the MESFET cathode TEO or so-called "FECTED" (field effect controlled TED) is that the injection current can be adjusted continuously by the gate bias voltage /6/.

DEVICE STRUCTURE

Fig. 1 shows a cross sectional view of the device. It consists of a 0.9 µm thick MOCVD-grown active n-layer (n = [illegible] cm^{-3}), a Schottky drain contact, an ohmic source contact, a 0.5 µm long Schottky gate with an integrated 10 pF capacitor to source. The device width is 400 µm.

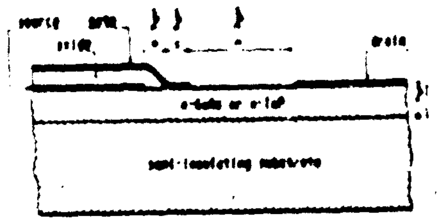

Fig. 1 Cross sectional view of the FECTED

EXPERIMENTAL RESULTS

Both the InP and the GaAs devices have been tested in microstrip circuits shown in Fig. 2. There are two identical stub terminated λ/4 long

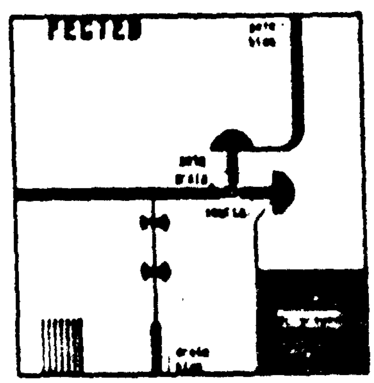

Fig. 2 Microstrip circuit configuration of a 37 GHz FECTED

50 Ω transmission lines providing capacitive impedances to both source and gate contacts. They compensate the various bonding wire inductances at upper Ka-band frequencies with a resonance at 37 GHz thereby producing a maximum reflection gain at that frequency. Amplification over almost 10 GHz has been measured with a GaAs FECTED mounted in this circuit as is shown in Fig. 3. A negative gate bias voltage of about -6V was applied to the device.

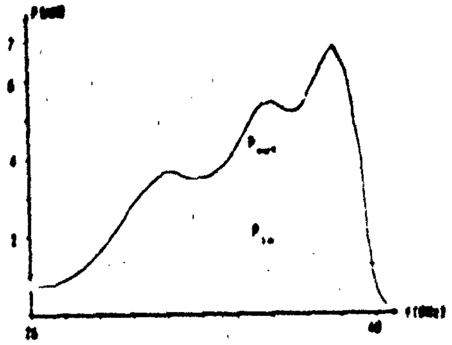

Fig. 3 Output and input power versus frequency of a FECTED reflection type amplifier

In order to produce free running oscillations a dielectric resonator had to be placed near the drain contact. The best oscillatory results have been summarized in the table shown below. These data have been recorded using pulsed drain bias voltages in order to avoid possible burn out.

Material	Drain Bias Pulse width	V_{DS}(V)	V_{GS}(V)	I(A)	eff.%	P(mW)	f(GHz)
GaAs	1us	7.0	5.0	0.15	5.3	56	28.4
GaAs	1us	6.1	-7.9	0.13	4.9	39	37.4
InP	1us	11.3	-4.3	0.17	2.9	55	34.8
GaAs	60us	6.7	-8.35	0.15	2.9	29.5	29.4
GaAs	60us	5.4	-9.1	0.144	3.8	29.9	37.3

Other devices with lower power levels have been operated CW. The data shown in the table are divided into short and long pulses-results. 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 devices as the power output remained unchanged when increasing the duty cycle from 10% to 40%. The results reported here exceed previously reported GaAs data by about 30 to 50% /7/.

Fig. 4 shows the spectral characteristic of a free running 8 mW CW operated FECTED oscillator.

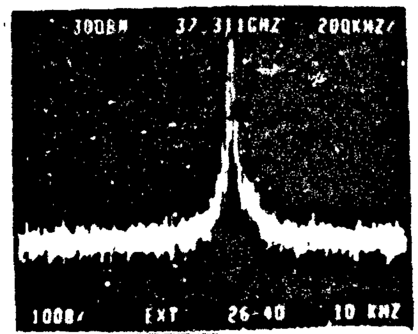

Fig. 4: Spectrum of an 8 mW FECTED oscillator

SUMMARY

We have demonstrated that planar GaAs and InP 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 as conventional TEOs and FETs are. At 29 and 34 GHz the highest output power levels ever obtained with lateral TEOs and FET oscillators and at 37 GHz the highest lateral TEO output power have been produced.

ACKNOWLEDGEMENTS

This work was supported in part by the Austrian Fonds zur Foerderung der wissenschaftlichen Forschung and by the US Army through its European Research Office. The authors would like to thank G. Hofmann, J. Katzenmayer and G. Rottmayr for fabrication of the devices and H. Lettenmayr for characterization of the epitaxial layers.

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IC-COMPATIBLE 45mW Ka-BAND GaAs TRANSFERRED-ELECTRON OSCILLATOR

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

The performance of a planar field effect controlled transferred electron oscillator has been significantly improved by reducing the length of the low field regions near drain and source. 45mW with 4·3% efficiency at 28·4GHz and 24mW with 3·2% at 37·4GHz have been obtained, which is a factor of 4·5 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.[1,2] The intense developments of mm-wave FETs also resulted in high performance oscillators producing 30mW at 34GHz with 30% efficiency[3] and in a 115GHz monolithic GaAs FET oscillator[4] which, however, produced a drastically reduced output power of only 0·1mW. This steep decrease of power cannot be explained alone by the $1/f^2$-law due to the transit-time limitation FETs are subject to. Other effects such as short channel effects,[5] current injection into the buffer layer or parasitic bipolar effects[6] 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.[7] 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 TEOs and FETs are suffering from.

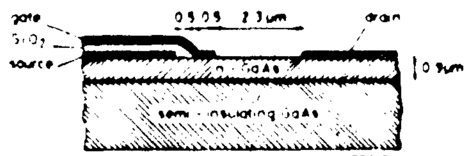

Fig. 1 *Cross-sectional view of FECTED*

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 MOCVD-grown active n-GaAs layer ($N_D = 5 \times 10^{16} cm^{-3}$), a Schottky drain contact, an ohmic source contact and a 0·5µm long overlapping Schottky gate separated from the source by a 500nm thick SiO_2 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 lengths of the low field regions outside the stationary high field domain much shorter than those in previously used devices.[8] This results in significantly smaller series resistances.

The new device have been tested in microstrip circuits identical to those used in previously performed experiments.[8] Fig. 2 shows the configuration of the test circuit. There are two identical resonators connected to source and gate, respectively. These are stub terminated ($\lambda/4 + \lambda/10$) long 50Ω transmission lines providing capacitive impedances in order to compensate for the various bonding wire inductances. In addition to these a dielectric resonator (f_R = 36GHz) is placed near the device needed for establishing stable oscillations. Without this resonator the device exhibits stable reflection gain of several dB from 30 to 40GHz with a 10dB gain peak at 37·4GHz.

Two modes of operation have been observed depending on the magnitude of the gate bias voltage. At $V_g = -5$V and $V_D \approx 6$V transit-time oscillations occur characterised 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 $V_g = -7$V the same device oscillated in the so-called[7,8] 'field effect controlled transferred electron device' or FECTED-mode characterised by a 'breathing' high field domain located underneath the gate and extending somewhat into the gate-drain region. This mode has also been called 'FET-mode' by Rolland *et al.*[9] 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 9GHz above the transit time frequency.

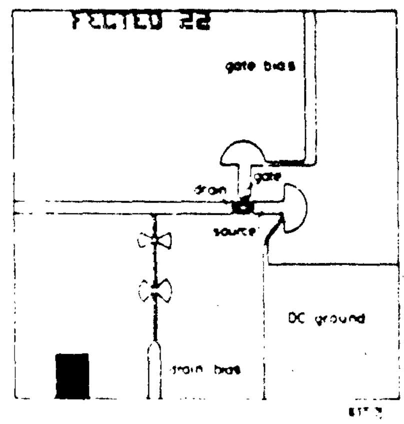

Fig. 2 *Microstrip layout of 37GHz oscillator*

To avoid possible burn-out the devices exhibiting the best data have been operated only with pulses up to 10µs. Lower doped devices with 30% lower drain currents have been operated CW producing 19mW with 2·3% efficiency at 28·4GHz and 15mW with 1·7% 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 like conventional TEOs and FETs are. At 37·4GHz the highest output power and efficiency ever obtained with lateral TEOs[10] and at 28·4GHz the highest output power ever obtained with lateral TEOs[10] and FET[3] oscillators have been achieved.

This work was supported in part by the Austrian Fonds zur Foerderung der wissenschaftlichen Forschung and by the US Army through its European Research Office.

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15th November 1988

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

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Abstract — An MIMIC-compatible transferred electron oscillator is investigated which utilizes the frequency-independent negative resistance of the stationary charge dipole domain that forms in the channel of a MESFET. Devices fabricated from GaAs and InP exhibit 56 mW at 29 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 FET's has resulted in high-performance oscillators capable of producing 30 mW at 34 GHz with 30 percent efficiency [1] and in a 115 GHz monolithic GaAs FET oscillator [2], which, however, produced a drastically reduced output power of only 0.1 mW. This steep decrease of power cannot be explained merely by the $1/f^2$ law due to the transit time limitation that FET's 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. TEO's exhibit lower efficiencies but require simpler loading circuits since they are two-terminal devices. They are much easier to manufacture because submicrometer dimensions are not needed. In addition TEO's are known for their superior noise performance. However, since conventional TEO's 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. MOCVD-grown 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 $2\cdot 10^{16}$ cm^{-3} and $6\cdot 10^{16}$ cm^{-3} for GaAs and [illegible]$\cdot 10^{16}$ 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 μm. Both the length of the Schottky gate and the distance between gate and source have been chosen to be 0.5 μm. The length of the active region (between gate and anode contact) was varied from 2.3 to 5 μm. The thickness of the semi-insulating substrate is 300 μm.

Manuscript received April 5, 1989; revised July 20, 1989. This work was supported in part by the Austrian Fonds zur Foerderung der wissenschaftlichen Forschung, by the Linz based company CIFEG, and by the U.S. Army through its European Research Office.

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IEEE Log Number 8931092.

0018-9480/89/1200-2093$01.00

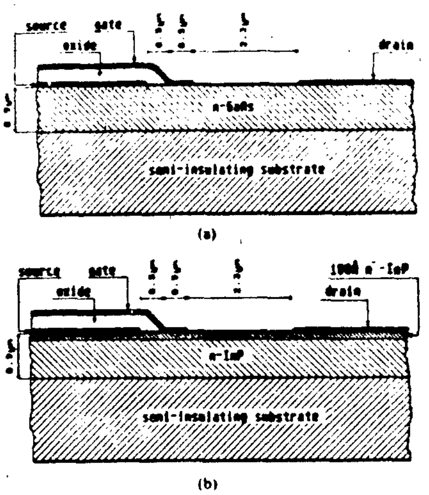


Fig. 1. Cross-sectional view of (a) GaAs and (b) InP devices.

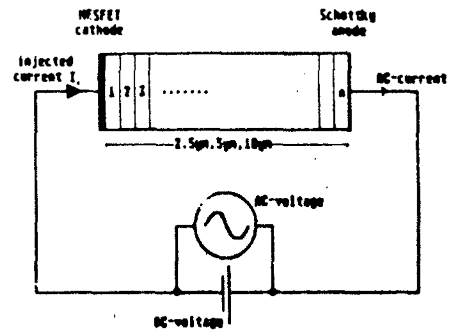


Fig. 2. Simulated device structure and circuit.

TABLE I

average doping level	$1\cdot 10^{15} - 5\cdot 10^{16}\ cm^{-3}$
device length	2.5 μm, 5 μm, 10 μm
DC-voltage	4.5 V - 20 V
amplitude of AC-voltage	4.0 V - 18 V
frequency	25 GHz - 60 GHz

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]:

$$v(E) = \frac{\mu E + v_s(E/E_0)^4}{1+(E/E_0)^4}. \qquad (1)$$

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 μm. 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_C 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 $N_D \cdot L$ product. The simulation parameters are summarized in Table I.

Fig. 3 shows a sequence of field and carrier distributions of a 5-μm-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 thus acts as a positive resistance, thereby contributing to loss. It also causes an upper frequency limit (RC 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.

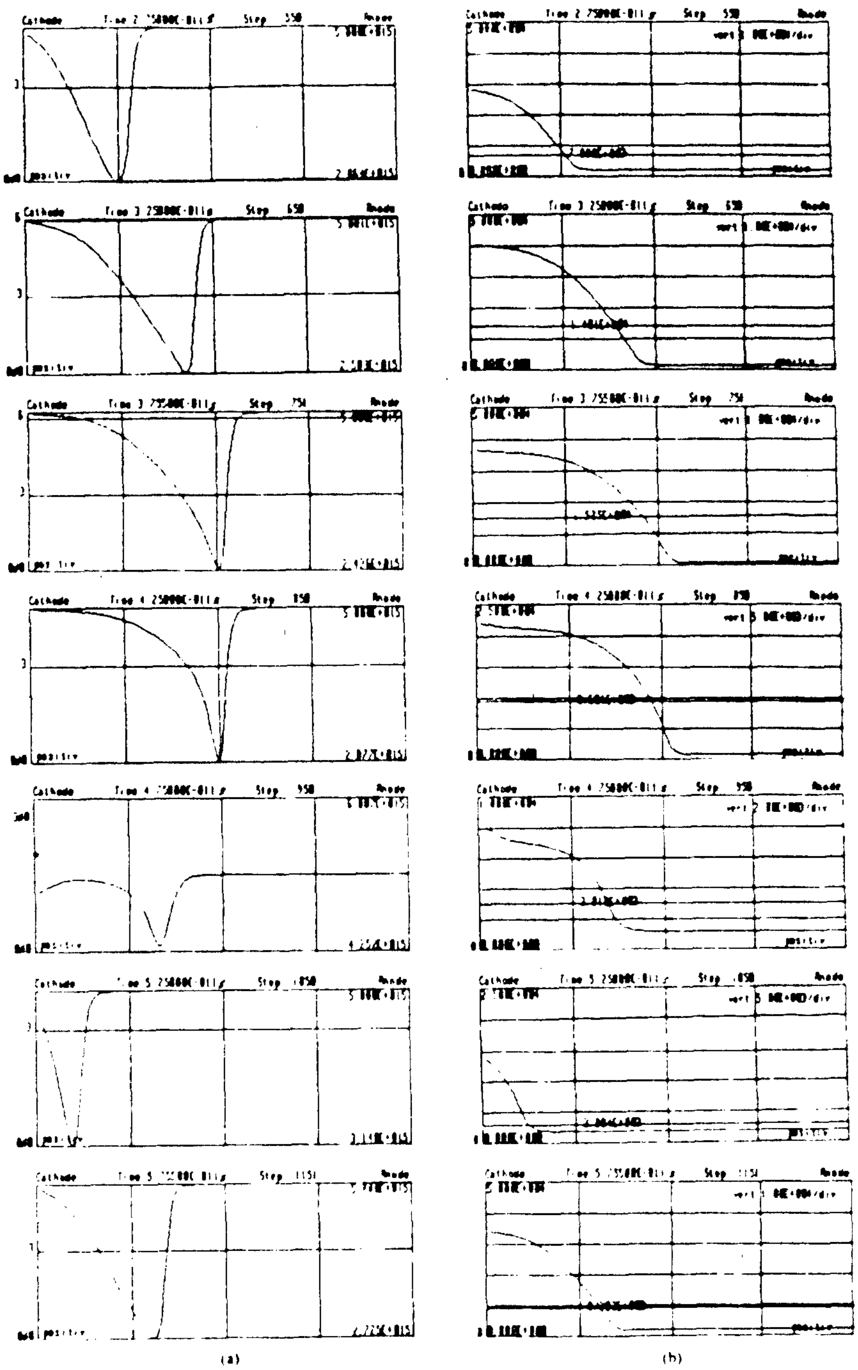
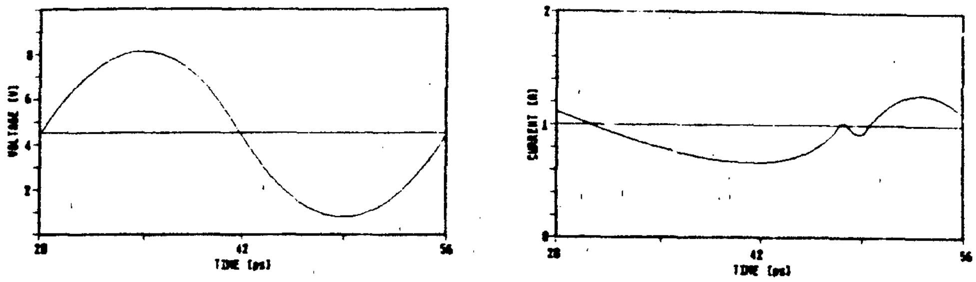
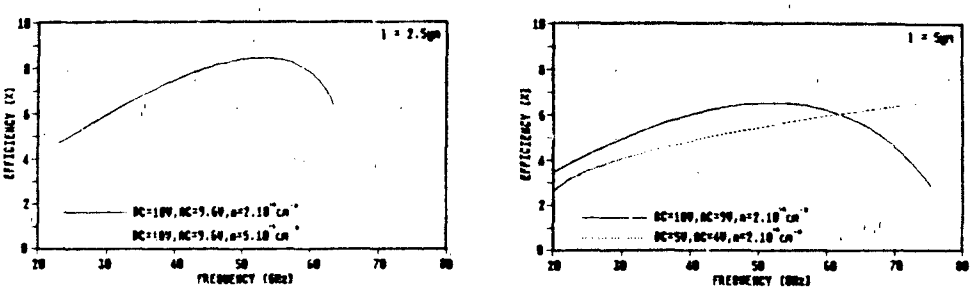


Fig. 3. (a) Calculated carrier concentration. (b) Field distribution. (*Continued*)



(c) (d)

Fig. 3. (*Continued*) (c) Voltage. (d) Current.



(a) (b)

Fig. 4. Calculated efficiencies versus frequency for different voltage and doping levels. (a) $l = 2.5$ μm; (b) $l = 5$ μm.

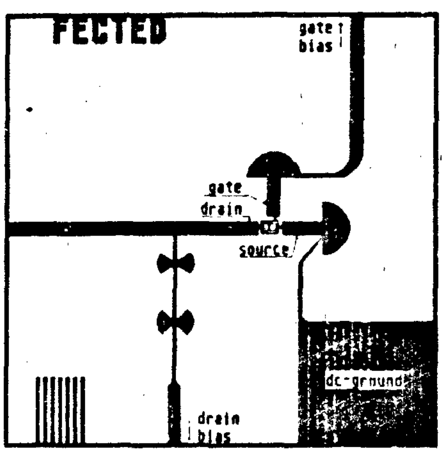


Fig. 5. Microstrip layout.

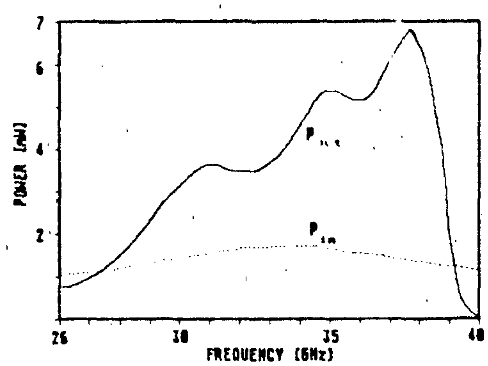


Fig. 6. Input and output powers versus frequency of a FECTED reflection-type amplifier.

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. 5. 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 $3\lambda/8$ 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

TABLE II

Material	Drain Bias Pulse Width	V_{DS} (V)	V_{GS} (V)	I (A)	eff %	P (mW)	f (GHz)
GaAs	1 µs	7.0	-5.6	0.15	5.3	56	28.4
GaAs	1 µs	6.1	-2.9	0.13	4.9	39	37.4
InP	1 µs	11.3	-4.3	0.17	2.9	55	34.4
GaAs	50 µs	6.7	-8.35	0.15	2.9	29.5	29.8
GaAs	50 µs	5.4	-9.1	0.144	3.3	29.8	37.3

voltage of -6 V have been applied to this device. Fig. 6 shows measured output power versus frequency with an input power level of approximately 1 mW.

In order to produce free-running oscillations, several resonance circuits have been tested. The best results have been achieved with dielectric resonators placed near the drain contact and by carefully adjusting the gate voltage. Since the frequency of oscillation is determined not only by the dielectric resonator alone but also by the device impedance, the frequency can be shifted by varying the gate bias voltage. Frequency tuning up to 200 MHz at a center frequency of 30 GHz and up to 500 MHz at 37 GHz has been observed.

Table II summarizes the best experimental results. The highest efficiency of a GaAs device at 28.4 GHz for short pulse operation was 5.3 percent. At 37 GHz the efficiency is only a bit smaller, showing the absence of the transit time limitation. 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 level of InP devices is in the 50 mW range.

In order to prevent burnout, the higher current devices 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 devices since the power output remains unchanged when increasing the duty cycle from 10 to 40 percent.

Fig. 7 shows the spectral characteristics of a free-running 8 mW CW-operated FECTED oscillator. By a crude 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 at very high frequencies since they are not transit time limited, as conventional TEO's and FET's are. At 29 GHz and 34 GHz the highest

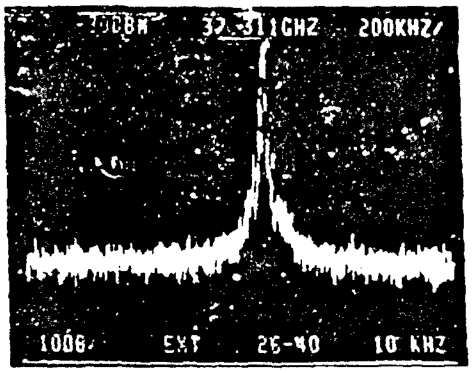


Fig. 7. Spectral characteristic of a free-running 8 mW CW-operated FECTED.

output power levels ever obtained with lateral TEO's and FET oscillators and at 37 GHz the highest lateral TEO 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 Ka-band frequencies are significantly lower than FET oscillator efficiencies but might become comparable at E-band and W-band frequencies due to the absence of the transit time limitation and to the simpler loading circuitry required by the two-terminal FECTED. However, intervalley scattering 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.

Acknowledgment

The authors thank G. Hofmann, J. Katzenmayer, and G. Rottmayr for fabrication of the devices; H. Lettenmayer for characterization of the epitaxial layers, and C. Schoenherr for assistance in the numerical studies.

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