above 8·3 GHz achieved at 10 mW/facet optical power level ($3{\cdot}4I_{th}$) exceeds that of conventional buried crescent lasers[4] and that of ridge waveguide lasers.[5]

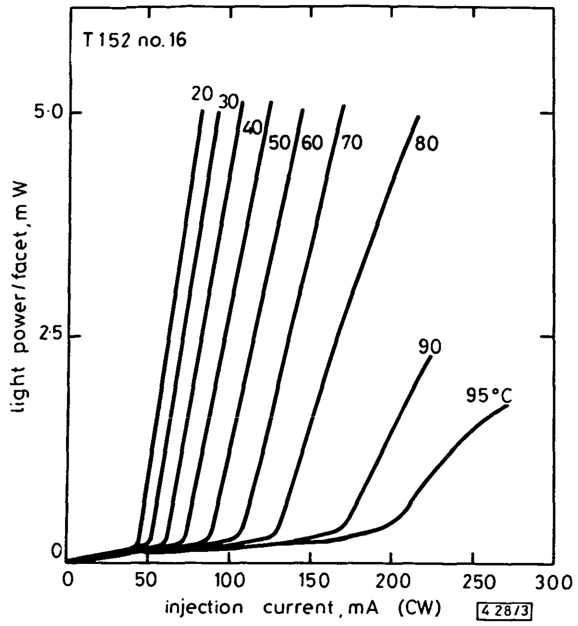

Fig. 3 *Temperature dependence of light power/injection current characteristics of a buried crescent laser under CW operation*

Discussion: In this letter wide-bandwidth and high-power 1·3 µm InGaAsP buried crescent lasers have been made with MOVPE-grown Fe-doped InP blocking layers that are demonstrated to be effective in reducing parasitic capacitances and leakage currents. With this laser structure, it should be possible to achieve wide-bandwidth operation (above 10 GHz) by reducing cavity length and contact pad size, and high-power operation (above 75 mW/facet) by improving the quantum efficiency from that of the present device structure.

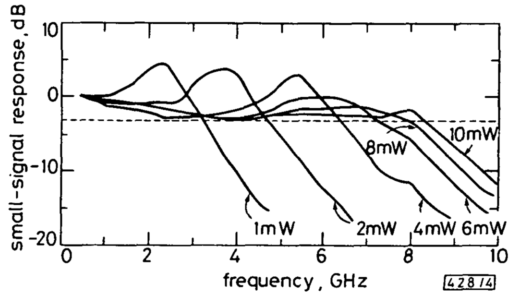

Fig. 4 *Room-temperature small-signal frequency response at various optical power levels*

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References

1 ISHIKAWA, H., IMAI, H., TANUHASHI, T., HORI, K. I., and TAKAHEI, K.: 'V-grooved substrate buried heterostructure InGaAsP/InP laser emitting at 1·3 µm wavelength', *IEEE J. Quantum Electron.*, 1982, **QE-18**, pp. 1704–1711

2 SAKAKIBARA, Y., HIGUCHI, H., OOMURA, E., NAKAJIMA, Y., YAMAMOTO, Y., GOTO, K., NAMIZAKI, H., IKEDA, K., and SUSAKI, W.: 'High-power 1·3 µm InGaAsP *P*-substrate buried crescent lasers', *J. Lightwave Technol.*, 1985, **LT-3**, pp. 978–984

3 WILT, D. P., LONG, J., DAUTREMONT-SMITH, W. C., FOCHT, M. W., SHEN, T. M., and HARTMAN, R. L.: 'Channelled-substrate buried-heterostructure InGaAsP/InP laser with semi-insulating OMVPE base structure and LPE regrowth', *Electron. Lett.*, 1986, **22**, pp. 869–870

4 OOMURA, E., HIGUCHI, H., SAKAKIBARA, Y., HIRANO, R., NAMIZAKI, H., SUSAKI, W., IKEDA, K., and FUJIKAWA, K.: 'InGaAsP/InP buried crescent laser diode emitting at 1·3 µm wavelength', *IEEE J. Quantum Electron.*, 1984, **QE-20**, pp. 866–874

5 TUCKER, R. S., and KAMINOW, I. P.: 'High-frequency characteristics of directly modulated InGaAsP ridge waveguide and buried heterostructure lasers', *J. Lightwave Technol.*, 1984, **LT-2**, pp. 385–393

MICROWAVE CHARACTERISATION OF 1 µm-GATE $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As/InP$ MODFETs

Indexing terms: Microwave devices and components, Field-effect transistors

We report microwave characterisation of nominally 1 µm-gate $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ (lattice-matched to InP) modulation-doped field-effect transistors (MODFETs). The $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ MODFETs have room-temperature extrinsic transconductances as high as 250 mS/mm. A room-temperature unity-current-gain cutoff frequency (f_T) of 22 GHz and an f_{max} of 35 GHz were measured for a 1·2 µm-gate MODFET.

Introduction: The modulation-doped field-effect transistor (MODFET) in the $Al_xGa_{1-x}As/GaAs$ system has been extensively investigated for high-speed digital and microwave device applications, demonstrating switching speeds of less than 10 ps,[1] room-temperature noise figures of 2·7 dB[2] at 62 GHz and room-temperature current-gain cutoff frequencies of 80 GHz.[3] $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ (lattice-matched to semi-insulating InP substrates) MODFETs have potential for yet higher frequency and higher-speed device applications. $Ga_{0.47}In_{0.53}As$ has high electron mobility,[4] high electron velocity[5,6] and a large separation in energy between the Γ and *L* valley (0·55 eV).[7] The $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ MODFET has the advantages of having higher room-temperature electron mobilities in the 2-D electron gas,[8] a larger conduction-band discontinuity (ΔE_c of $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As \sim 0{\cdot}5$ eV),[9,10] lower persistent photoconductivity[11] and the possibility of higher 2-D electron sheet concentrations[12] over the $Al_xGa_{1-x}As/GaAs$ system.

The first AlInAs/GaInAs MODFETs reported had 90 mS/mm transconductances for 1 µm-gate devices.[13] High-

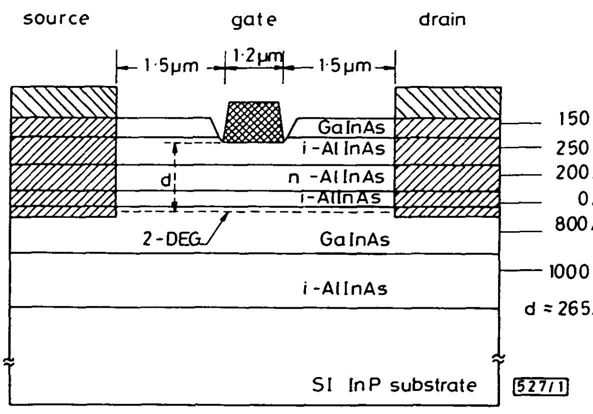

Fig. 1 *Cross-sectional view of depletion-mode recessed-gate $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As/InP$ MODFET*

$Ga_{0.47}In_{0.53}As$ has background carrier concentration of $\simeq 1 \times 10^{16}\,cm^{-3}$ *n*-type
Hall measurements indicate room-temperature mobilities between 8000–10 000 $cm^2/V\,s$ with sheet carrier concentrations of $1{\cdot}5 \times 10^{12}\,cm^{-2}$

transconductance (250 mS/mm at room temperature) depletion- and enhancement-mode 1 μm-gate AlInAs/GaInAs MODFETs were successfully fabricated using a recessed gate structure with a layer of undoped AlInAs under the gate metal.[14] In this letter we report microwave characterisation of these devices.

Results: A cross-sectional view of the AlInAs/GaInAs MODFET is shown in Fig. 1. The epilayers are MBE-grown lattice-matched to InP substrates. Epilayer growth and device fabrication is described elsewhere.[14]

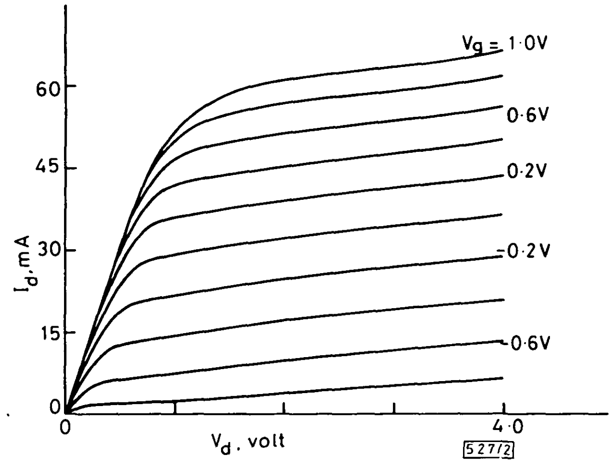

Fig. 2 *Current/voltage characteristics of 1·2 μm-gate-length 200 μm-gate-width $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As/InP$ MODFET*

Room-temperature extrinsic transconductance is 200 mS/mm at $V_g = 0$ V and with a current density of 150 mA/mm. Source resistance is 1·4 Ω mm. Maximum current density is 300 mA/mm

The current/voltage characteristics of the 1·2 μm-gate MODFET illustrated in Fig. 1 is shown in Fig. 2. The microwave scattering parameters were measured from 1 to 20 GHz. The equivalent-circuit model used to fit the measured scattering parameters is shown in Fig. 3 with the circuit element values listed in Table 1. Typical circuit element values for a 1 μm-gate AlGaAs/GaAs MODFET are listed for comparison.[15]

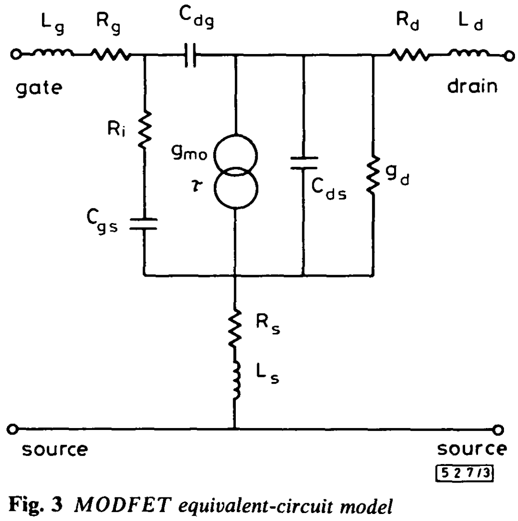

Fig. 3 *MODFET equivalent-circuit model*

Fig. 4 shows the current-gain/frequency and power-gain/frequency curves for the 1·2 μm AlInAs/GaInAs MODFET shown in Fig. 1. The current-gain/frequency curve is extrapolated at a slope of −6 dB/octave to give a unity-current-gain cutoff frequency f_T of 22 GHz. The power-gain/frequency curve is extrapolated at −6 dB/octave to give a maximum available gain f_{max} of 35 GHz.

Conclusions: This letter reports the first microwave measurements of AlInAs/GaInAs MODFETs. An f_T of 22 GHz for a 1·2 μm-gate $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As/InP$ MODFET compared to an f_T of 18 GHz for a 1·0 μm-gate AlGaAs/GaAs MODFET[15] represents an improvement of 20–30%. Optimised device structures will further improve device performance. State-of-the-art values for extrinsic DC transconductances for 1 μm-gate $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As/InP$ MODFETs are 440 mS/mm at room temperature and 700 mS/mm at 77 K.[16] The enhanced electron velocities in $Ga_{0.47}In_{0.53}As$ and the large conduction-band discontinuity of ~0·5 eV between $Al_{0.48}In_{0.52}As$ and $Ga_{0.47}In_{0.53}As$, helping to confine energetic electrons, should yield even higher frequency performance at short gate lengths.

Table 1 CIRCUIT PARAMETER VALUES FOR EQUIVALENT CIRCUIT SHOWN IN FIG. 3

	AlGaAs/GaAs* 1 μm gate $I_{ds} = 30$ mA $V_{ds} = 4$ V $V_{gs} = -0.2$ V	AlInAs/GaInAs 1·2 μm gate $I_{ds} = 33$ mA $V_{ds} = 3$ V $V_{gs} = 0$ V
g_{mo}, mS/mm	140	400
C_{gs}, pF/mm	1·3	3·3
R_0, Ω mm	220	140
R_{in}, Ω mm	7·0	4·2
R_s, Ω mm	1·5	0·9
R_d, Ω mm	0·84	0·9
C_{dg}, pF/mm	0·09	0·08
C_{ds}, pF/mm	0·16	0·28
T_t, ps	2·4	3·1

* Douglas Arnold *et al.*, University of Illinois, IEEE TED, 1984

Circuit parameters are listed for 1·2 μm-gate $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As/InP$ and for a 1·0 μm AlGaAs/GaAs MODFET for comparison

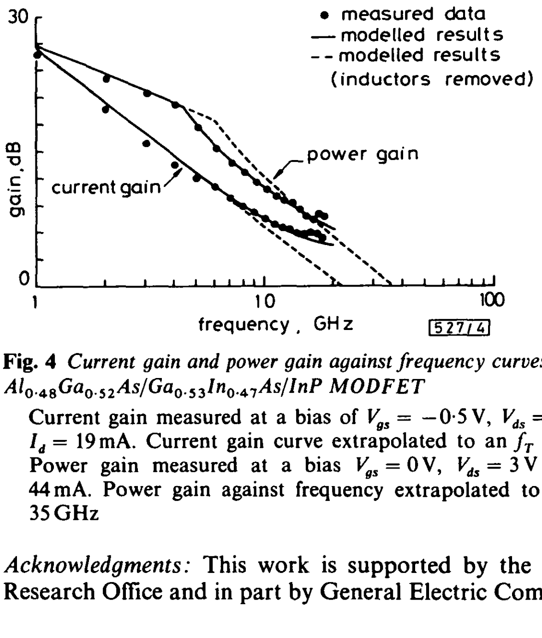

Fig. 4 *Current gain and power gain against frequency curves for 1·2 μm $Al_{0.48}Ga_{0.52}As/Ga_{0.53}In_{0.47}As/InP$ MODFET*

Current gain measured at a bias of $V_{gs} = -0.5$ V, $V_{ds} = 2.0$ V and $I_d = 19$ mA. Current gain curve extrapolated to an f_T of 22 GHz. Power gain measured at a bias $V_{gs} = 0$ V, $V_{ds} = 3$ V and $I_d = 44$ mA. Power gain against frequency extrapolated to an f_{max} of 35 GHz

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References

1 SHAH, N. J., PEI, S., TU, C. W., and TIBERIO, R. C.: 'Gate-length dependence of the speed of SSI circuits using submicrometer selectively doped heterostructure transistor technology', *IEEE Trans.*, 1986, **ED-33**, pp. 543–547

2 DUH, K. H. G., CHAO, P. C., SMITH, P. M., LESTER, L. F., LEE, B. R., and HWANG, J. C. M.: 'Millimeter wave low noise HEMTs'. Presented at 44th annual dev. res. conf., 23–25 June 1986, University of MA at Amherst, USA

3 CHAO, P. C., SMITH, P. M., MISHRA, U. K., PALMATEER, S. C., DUH, K. H. G., and HWANG, J. C. M.: 'Quarter-micron low-noise high electron

mobility transistors'. Proceedings of IEEE/Cornell conf. on advanced concepts in high speed semiconductor devices and circuits, 1985, pp. 163–169
4 OLIVER, J. D. JR., and EASTMAN, L. F.: 'Liquid phase epitaxial growth and characterization of high purity lattice matched $Ga_xIn_{1-x}As$ on ⟨111⟩B InP', *J. Electron. Mater.*, 1980, **9**, pp. 693–712
5 BANDY, S., NISHIMOTO, C., HYDER, S., and HOOPER, C.: 'Saturation velocity determination for $In_{0.53}Ga_{0.47}As$ field effect transistors', *Appl. Phys. Lett.*, 1981, **38**, pp. 817–819
6 GHOSAL, A., CHATTOPADHYAY, D., and PURKAIT, N. N.: 'Hot-electron velocity overshoot in $Ga_{0.47}In_{0.53}As$', *ibid.*, 1984, **44**, pp. 773–774
7 CHENG, K. Y., CHO, A. Y., CHRISTMAN, S. B., PEARSALL, T. P., and ROWE, J. E.: 'Measurement of the Γ-L separation in $Ga_{0.47}In_{0.53}As$ by ultraviolet photoemission', *ibid.*, 1982, **40**, pp. 423–425
8 GRIEM, T., NATHAN, M., WICKS, G. W., and EASTMAN, L. F.: 'High mobility modulation doped $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ structures'. Inst. Phys. Conf. Ser. no. 75, Chap. 5, pp. 367–371, presented at inter. symp. on GaAs and related compounds, Biarritz, France, 1984
9 PEOPLE, R., WECHT, K. W., ALAVI, K., and CHO, A. Y.: 'Measurement of the conduction-band discontinuity of molecular beam epitaxial grown $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$, *N-n* heterojunction by *C-V* profiling', *Appl. Phys. Lett.*, 1983, **43**, pp. 118–120
10 WELCH, D. F., WICKS, G. W., and EASTMAN, L. F.: 'Calculation of the conduction band discontinuity for $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ heterojunction', *J. Appl. Phys.*, 1984, **55**, pp. 3176–3179
11 GRIEM, T., NATHAN, M., WICKS, G. W., HUANG, J. C., CAPANI, P. M., and EASTMAN, L. F.: 'High conductance and low persistent photoconductivity in $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ modulation-doped structures with pinchoff capabilities', *J. Vac. Sci. & Technol.*, 1985, **B2**, pp. 655–656, presented at 3rd int. conf. on MBE, San Francisco, CA, 1–3 Aug., 1984
12 ITOH, T., GRIEM, T., WICKS, G. W., and EASTMAN, L. F.: 'Sheet electron concentration at the heterointerface in $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ modulation-doped structures', *Electron. Lett.*, 1985, **21**, pp. 373–374
13 PEARSALL, T. P., HENDEL, R., O'CONNOR, P., ALAVI, K., and CHO, A. Y.: 'Selectively-doped $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ heterostructure field effect transistor', *IEEE Electron Device Lett.*, 1983, **EDL-4**, pp. 5–8
14 ITOH, T., BROWN, A. S., CAMNITZ, L. H., WICKS, G. W., BERRY, J. D., and EASTMAN, L. F.: 'Depletion and enhancement-mode $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ modulation doped field-effect transistors with a recessed gate structure'. Inst. Phys. Conf. Ser. no. 79, Chap. 10, pp. 571–576, presented at 12th int. symp. on GaAs and related compounds, Karvizawa, Japan, 1985
15 ARNOLD, D. J., FISCHER, R., KOPP, W. F., HENDERSON, T. S., and MORKOC, H.: 'Microwave characterization of (Al, Ga)As/GaAs modulation-doped FET's: bias dependence of small-signal parameters', *IEEE Trans.*, 1984, **ED-31**, pp. 1399–1402
16 HIROSE, K., OHATA, K., MIZUTANI, T., ITU, P., and OGAWA, M.: '700 mS/mm 2DEGFETs fabricated from high mobility MBE-grown *n*-AlInAs/GaInAs heterostructures'. Inst. Phys. Conf. Ser. no. 79, Chap. 10, pp. 529–534, presented at 12th int. symp. on GaAs and related compounds, Karvizawa, Japan, 1985

SIMPLE METHOD FOR MEASURING HOT-ELECTRON TEMPERATURE IN GaAs

Indexing terms: Semiconductor devices and materials, Hot electrons

A simple method is proposed to measure the hot-electron temperature, using an Au-GaAs Schottky barrier diode. The obtained temperature of electrons under the electric field of 500 V/cm and 1100 V/cm are 316 K and 336 K, respectively, while the samples are kept at room temperature.

Recently, more and more attention has been paid to real-space transfer of electrons in heterojunction structures. Some new device concepts based on hot-electron transfer between two conducting layers in an AlGaAs/GaAs heterostructure have been reported, such as NERFET, CHINT etc. One of the important parameters in these devices is the hot-electron temperature. Many methods have been used to measure the hot-electron temperature in semiconductors, for example, the tunnelling method,[1] luminescence and mobility measurements.[2,3] In this letter we propose a simple method, using an Au-GaAs Schottky barrier diode, to measure the temperature of hot electrons heated by a high electric field. An undoped GaAs layer with thickness 2·4 μm is obtained by LPE on the (100) face of a Cr-doped semi-insulating GaAs substrate. The sample shown in Fig. 1 is prepared by a standard photolithographic technique. Electrodes 1 and 2 were used for conducting the current across the sample to heat the electrons. Contact 4, which is made by evaporating Au, together with GaAs form a Schottky barrier diode.

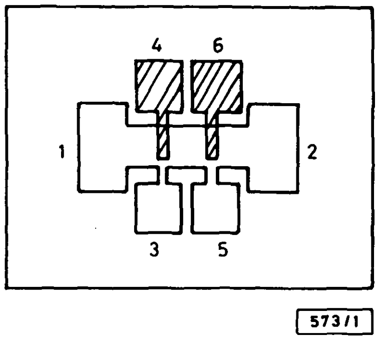

Fig. 1 *Top view of sample*

According to the thermionic emission theory, the I_j/V_j characteristics of a Schottky barrier are given as follows:

$$\ln I_j = \ln I_0 + qV_j/nkT_e \quad (1)$$

The electron temperature can be determined from the slope of the ln I_j/V_j characteristics. All measurements were made using pulse voltages to prevent lattice heating. The duration of the heating voltage pulse applied between contacts 1 and 2 is 25 μs and there are 100 pulses per second. The voltage pulse across the Au-GaAs Schottky diode is measured for 20 μs while the heating pulse is being applied. The ln I_j/V_j characteristics of an Au-GaAs Schottky diode with the heating electric field as a variable parameter are shown in Fig. 2. Samples are kept at room temperature. An undesirable bias voltage V caused by misalignment of electrodes 3 and 4 has been corrected. It can be seen that the ln I_j/V_j characteristics under zero heating electric field agree perfectly with eqn. 1, and the ideal factor n was found to be 1·80. Eqn. 1 is still a good description for ln I_j/V_j characteristics in the large forward-bias range when a high electric field is applied. The obtained temperature of electrons under the electric fields of 500 V/cm and 1100 V/cm are 316 K and 336 K, respectively. For measurements made at 77 K, the temperatures of electrons under electric fields of 600 V/cm and 1100 V/cm are 100 K and 127 K, respectively. These results are consistent with those given by luminescence methods.

Compared with other methods the Schottky barrier diode method can be used to measure the temperature of hot elec-

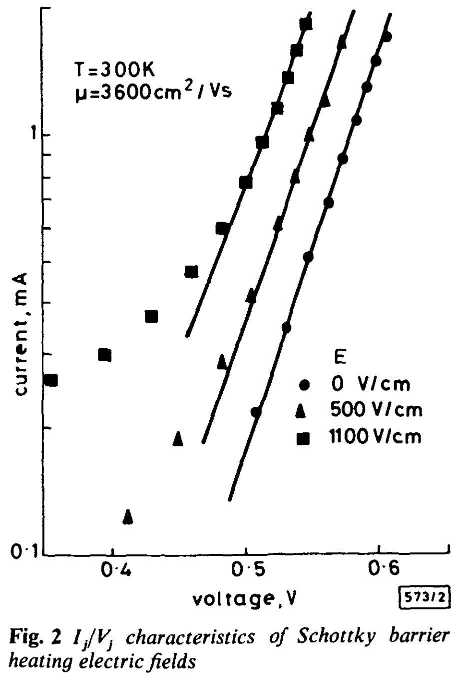

Fig. 2 I_j/V_j *characteristics of Schottky barrier diode under various heating electric fields*