ELECTRON TRAPS IN BULK AND EPITAXIAL GaAs CRYSTALS

Indexing terms: Electron traps, Gallium arsenide, III–V semiconductors

Fifteen different electron traps have been characterised in v.p.e., l.p.e., m.b.e. and bulk-grown GaAs from d.l.t.s. experiments. An accurate description of each level is given, and allows a fruitful comparison with fragmentary previous data. A catalogue of these electron traps is provided as a working tool.

The purposes of this letter are to present accurate data on electron traps detected in GaAs grown by different techniques (v.p.e., l.p.e., m.b.e. and bulk material), to show how it is actually possible to compare them with other data given in the literature and, finally, to provide a catalogue of them as a working tool for characterisation research.

The d.l.t.s. experiment[1] has been extensively used to measure the thermal emission rates $e_n(T)$ of levels as a function of temperature. It is well known that the theoretical expression of $e_n(T)$ includes the value of the capture cross-section σ_n and of the ionisation energy E_i corresponding to a given level. But it should be noticed that σ_n may be thermally activated with an activation energy E_b;[2] further, E_i has been shown to vary linearly as a function of temperature, with a corresponding slope denoted by α in a previous paper.[3] These two corrections lead to the following expression:

$$e_n(T) = \gamma_n T^2 (\sigma_{n\infty} g_n (\exp \alpha/R) \exp \left(-\frac{E_{i0}+E_b}{kT}\right)$$

where $\sigma_{n\infty}$ is the extrapolated value of σ_n for $T=\infty$, E_{i0} is the extrapolated value of E_i for $T=0$, g_n is the degeneracy factor and γ_n is a constant equal to $2{\cdot}28\times 10^{20}\,\mathrm{cm^{-2}\,s^{-1}}\,K^{-2}$ in GaAs. The plot of T^2/e_n as a function of $1/T$ yields $\sigma_\infty g_n$ exp (α/k) (denoted σ_{na}), as well as $E_{i0}+E_b$ (denoted E_{na}); these two parameters, σ_{na} and E_{na}, are actually the 'signature' of a trap, even if they do not have a direct physical meaning.

In fact, the best way to compare the results obtained in different laboratories on different materials is to give the whole T^2/e_n-against-$1/T$ curve; Fig. 1 clearly displays the data on all the different levels from this point of view. The characteristic emission parameters E_{na}, σ_{na} for electron traps in GaAs, together with information about the experimental conditions in which they have been observed and tentative identifications between traps reported by different laboratories, are summarised in Table 1.[4]

It turns out that we have observed fifteen electron traps from studies on a few tens of samples. The bulk material usually has many; only some are always present in as-grown v.p.e. or m.b.e. material, while none of them is seen in undoped, as-grown l.p.e. material.

It is worth noticing that trap EL2 (=ET1 = EB2 = ES1), which is the dominant one in v.p.e. and bulk material, is completely absent in m.b.e. layers. A lot of work has been devoted to the identification of this level. Especially, we have tried to check if it could be due to oxygen substitutional on As sites: outdiffusion of this defect has been studied,[5] and its electrical properties have been observed to vary as a function of the composition of the ternary $Ga_{1-x}In_xAs$.[6] The results are not fully consistent with the hypothesis O_{As}.

We have noticed that the concentration of traps EL3, EL5 and EL12 vary in a wide range according to growth conditions and are rather easily decreased by annealing.[5] This suggests that they are point defects or point-defects/impurity complexes. On the other hand, L11 is not affected by heat treatment and could thus be an impurity.

In contrast to the other levels, trap EL16 is acceptor-like, according to its small electron capture cross-section; from other studies,[7] it is believed to be responsible for the low-frequency noise spectrum in devices, with a cut-off frequency in the range 10^4–10^6 Hz.

One of the striking results is that v.p.e., m.b.e. and bulk-grown materials have many different electron traps, while, at the same time, only a few of them are common to the different methods of crystal growth. For instance, L6 (observed in bulk GaAs) and L7 (in m.b.e.) could be the same defect, which is, however, not observed in v.p.e.; L10 (m.b.e.) and L11 (v.p.e.) could be the same level, not yet seen in the bulk material; finally, L2 and L3 are seen both in v.p.e. and bulk GaAs, but not in m.b.e. In view of these observations, it

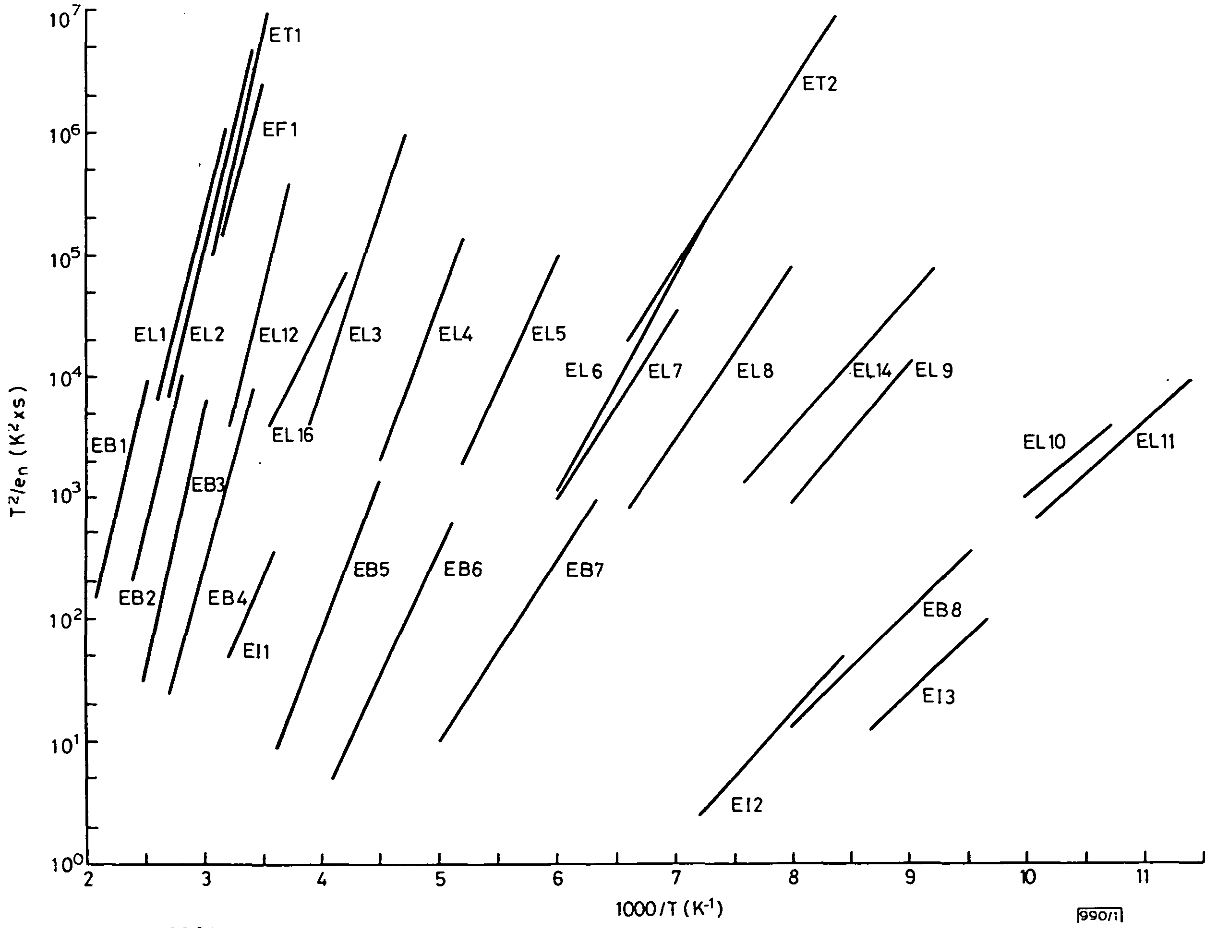

Fig. 1 *Plots of T^2/e_n as function of $1/T$ for all electron traps*

ET = University of Tokyo, ES = University of Sheffield, EF = Univeristy of Florida, EI = Institut für Angewandte Festkörperphysik, EB = Bell Telephone Laboratories, EL = this work. The curves EB giving Lang's results are extrapolated from his d.l.t.s. spectra. Larger versions of this Figure are available on request

Table 1 PARAMETERS E_{na} AND σ_{na} OF TRAPS CALCULATED FROM FIG. 1

Label (Fig. 1)	Reference and alternative labels	Activation energy E_{na}, eV	Emission section σ_{na}, cm^2	Observations	Possible comparisons
ET1	(14)	0·85	$6{\cdot}5\times10^{-13}$	Bulk material	
ET2	(14)	0·3	$2{\cdot}5\times10^{-15}$	Bulk material	
ES1	(13)	0·83	$1{\cdot}0\times10^{-13}$	Bulk material	
EF1	(15)	0·72	$7{\cdot}7\times10^{-15}$	Cr doped bulk mat.	
EI1	(20)	0·43	$7{\cdot}3\times10^{-16}$	V.P.E. mat.	
EI2	(20)	0·19	$1{\cdot}1\times10^{-14}$	V.P.E. mat.	
EI3	(20)	0·18	$2{\cdot}2\times10^{-14}$	V.P.E. mat.	
EB1	(16)	0·86	$3{\cdot}5\times10^{-14}$	Cr doped L.P.E. mat.	
EB2	(16)	0·83	$2{\cdot}2\times10^{-13}$	As grown V.P.E. mat.	
EB3	(12) (E5)	0·90	$3{\cdot}0\times10^{-11}$	Electron irradiated mat.	
EB4	(12) (E4)	0·71	$8{\cdot}3\times10^{-13}$	Electron irradiated mat.	
EB5	(17) (M4)	0·48	$2{\cdot}6\times10^{-13}$	As grown M.B.E. mat.	
EB6	(12) (E3)	0·41	$2{\cdot}6\times10^{-13}$	Electron irradiated mat.	
EB7	(17) (M3)	0·30	$1{\cdot}7\times10^{-14}$	As grown M.B.E. mat.	
EB8	(17) (M1)	0·19	$1{\cdot}5\times10^{-14}$	As grown M.B.E. mat.	
EB9	(12) (E2)	0·18	Imprecise	Electron irradiated mat.	
EB10	(12) (E1)	0·12	Imprecise	Electron irradiated mat.	
EL1		0·78	$1{\cdot}0\times10^{-14}$	Cr doped bulk mat.	
EL2	(10) (A)	0·825	$(0{\cdot}8–1{\cdot}7)\times10^{-13}$	V.P.E. material	EL2 = ET1 = ES1 = EB2
EL3	(10) (B)	0·575	$(0{\cdot}8–1{\cdot}7)\times10^{-13}$	V.P.E. material	
EL4		0·51	$1{\cdot}0\times10^{-12}$	As grown M.B.E. mat.	EL4 = EB5
EL5	(10) (C)	0·42	$(0{\cdot}5–2{\cdot}0)\times10^{-13}$	V.P.E. mat.	EL5 = EB6(?)
EL6		0·35	$1{\cdot}5\times10^{-13}$	Bulk material	EL6 = ET2
EL7		0·30	$7{\cdot}2\times10^{-15}$	As grown M.B.E. mat.	EL7 = EB7; EL7 = EL6(?)
EL8	(18) (D)	0·275	$7{\cdot}7\times10^{-15}$	V.P.E. mat.	
EL9	(18) (E)	0·225	$6{\cdot}8\times10^{-15}$	V.P.E. mat.	
EL10		0·17	$1{\cdot}8\times10^{-15}$	As grown M.B.E. mat.	EL10 = EB8
EL11	(18) (F)	0·17	$3{\cdot}0\times10^{-16}$	V.P.E. mat.	EL11 = ET3 = EL10(?)
EL12	(18) (A′)	0·78	$4{\cdot}9\times10^{-12}$	V.P.E. mat.	EL12 = EB4(?)
EL14		0·215	$5{\cdot}2\times10^{-16}$	Bulk material	
EL15		0·15	$5{\cdot}7\times10^{-13}$	Electron irradiated mat.	EL15 = EB9
EL16		0·37	$4{\cdot}0\times10^{-18}$	V.P.E. mat.	

seems that most of these levels could be due to complex defects, and that the temperature of growth influences their formation, but is not the single important factor coming into the picture. Since all the methods favour As-rich growth,[17, 21] the basic defect entering the complexes may be either the Ga vacancy or the As interstitial.[7]

A deep-level impurity, important in applications, is chromium. It is not clear whether one or several defects are associated to this element, and whether their formation is influenced by the different growth techniques. Further, infrared photoluminescence,[9] s.c.l.c.,[10] photocapacitance[11] and photoconductivity[19] measurements from *n*-type or semi-insulating Cr-doped samples are not in agreement, as far as the position of the Cr level in the gap is concerned. Further study is still needed to clarify the different data and to determine the exact electrical properties in *n*-type, as well as in semi-insulating GaAs material, this last material being of first importance for making devices such as GaAs field-effect transistors or integrated circuits.

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GaAs M.E.S.F.E.T.: A HIGH-SPEED OPTICAL DETECTOR

Indexing terms: Optical-communication equipment, Photodetectors, Schottky-gate field-effect transistors

The application of a GaAs m.e.s.f.e.t. as a high-speed optical detector has been investigated and compared with the result of a fast a.p.d.

For dispersion measurements on optical fibres with low dispersion, very-high-speed optical detectors are needed. In comparison with the fastest known avalanche photodiodes, the GaAs m.e.s.f.e.t. seems to be advantageous.

We investigated a 4-gate m.e.s.f.e.t. with a gatewidth of 800 μm and a gate length of 1 μm.*[1] The light source was a pulsed s.h. GaAs laser with a wavelength of 901 nm,† a stripe-width of 75 μm and a stripe thickness of 2 μm. The laser was imaged (1:1) onto the m.e.s.f.e.t., with the stripe parallel to the gates. So it was possible to focus the laser onto the four gates separately. Fig. 1 shows the electrical set-up.

The m.e.s.f.e.t. was mounted in a thick-film circuit with gate and drain connected to 50 Ω striplines, and the source connected to ground. The risetime of the whole electrical circuit following the s.m.a. drain plug on the thick-film circuit to the oscilloscope was measured with a fast t.d.r., and was 26 ps.

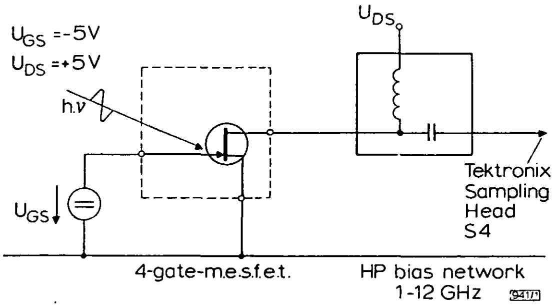

Fig. 1 *Electrical measurement set-up*

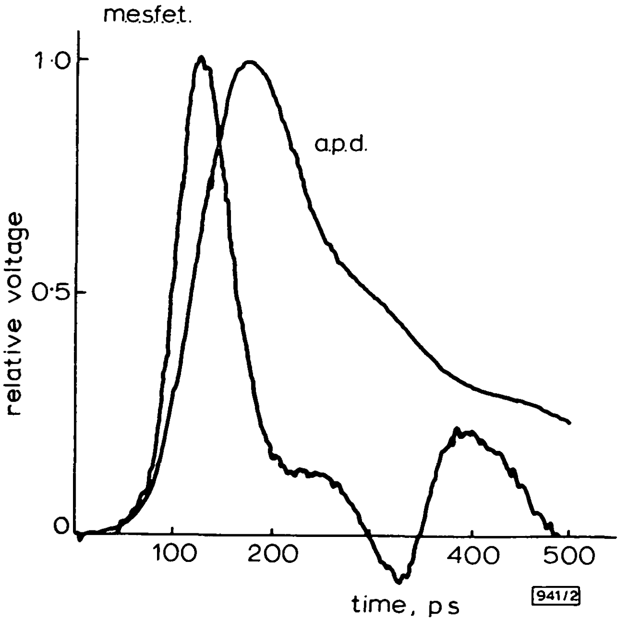

Fig. 2 *Pulse forms obtained for m.e.s.f.e.t. and a.p.d.*

* Made by the Institut für Halbleitertechnik der RWTH, D 51 Aachen, Templergraben 55, W. Germany

† Optel CL 1006, Optel GmbH, D 2 Norderstedt 3, Postfach 3428, W. Germany

The optimal gate–source voltage and drain–source voltage of the m.e.s.f.e.t. were found to be −5 and +5 V, respectively. Thus the gate–source voltage is more negative than the pinch-off voltage (−2·5 V), so the f.e.t. was completely nonconducting.

Fig. 2 shows the measured pulses obtained with the circuit according to Fig. 1, and, for comparison, we depict the pulse obtained with the fastest a.p.d. (NEC V 384) we had. For the measurement, m.e.s.f.e.t. and a.p.d. were alternately connected to the same circuit and mounted in the same position. The a.p.d. was biased with 80 V to get the fastest pulse response. The two pulses in Fig. 2 were normalised to the same height. Table 1 shows the real pulse heights, the rise-times and halfwidths. The times are not system response-time corrected.

Table 1

	Pulse height	t_r (10% to 90%)	$t_{0\cdot5}$
		ps	ps
M.E.S.F.E.T.	5	46	73
A.P.D.	75	74	178

For the four gates of the m.e.s.f.e.t. we found four active regions when scanning its surface with the laser image. All of the four gates had nearly the same pulse response. With increasing incident light power, the pulse broadened. Illuminating the whole crystal simultaneously with the laser pulse, we observed a pulse with the same risetime, but with a long tail. We could not determine the actual width of the light pulse, because we had no access to a streak camera.

The GaAs of the m.e.s.f.e.t. has a low quantum efficiency at the laser wavelength of 901 nm used, from the long penetration depth. It may be expected that, for a wavelength of 850 nm, the quantum efficiency will be higher and the pulse response faster.

We see a further application of the m.e.s.f.e.t. as an optical receiver not only in optical-measurement systems, but also for classical optics, where a high local resolution may be achieved.

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THICK-FILM 3-STAGE M.I.C. IMPATT-DIODE-AMPLIFIER ON FERRITE

Indexing terms: Impatt diodes, Microwave amplifiers, Microwave integrated circuits, Thick-film circuits

A 3-stage hybrid m.i.c. gallium-arsenide impatt-diode amplifier is described with an output of 1·05 W at 9·2 GHz, a large-signal gain of 21 dB and a bandwidth to −3 dB greater than 1 GHz; the amplifier is stable at all input levels. The concept of an effective radius, first proposed to explain the properties of disc capacitors, has been used successfully in the circulator design. Close attention has been paid to screening the unencapsulated diodes to prevent r.f. radiation and to incorporating resistive-loading circuits to suppress spurious out-of-band oscillations.

Introduction: This letter describes the design and fabrication of a small X-band impatt-diode amplifier with an approximate gain of 20 dB, a 10% bandwidth and an output power of about 1 W. To minimise overall size and to avoid interfacing