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ABSTRACT

A deep level transient conductance spectrometer for high resistivity semiconductors, using a radiofrequency (~ 40 MHz) marginal oscillator as a conductance detector, is described. Spectra are generated by periodically filling deep level trapping centres with carriers stimulated by a pulsed GaAs laser, and processing the trap-emptying conductance signal through an exponential Miller correlator as the sample temperature is slowly ramped.

Simple capacitive coupling of samples to the oscillator tank circuit eliminates problems such as unwanted defect annealing and other material changes often associated with the high temperature techniques necessary for ohmic contact formation. Representative deep level spectra are given for semi-insulating Bridgman-grown CdTe.

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CADMIUM TELLURIDES; OSCILLATORS; SEMICONDUCTOR MATERIALS; SPECTROMETERS; TRAPS

CONTENTS

1. INTRODUCTION

Deep level transient junction capacitance spectroscopy (DLTCS) using semiconductor diode structures [Miller *et al.* 1977] is a well-established technique for the measurement of electrically active, deep level defects in materials having a concentration < 0.1 of the background shallow level centre concentration. However, the method fails for semi-insulating or well-compensated semiconductors.

This difficulty can be overcome by using optical transient conduction spectroscopy (OTCS), as described by Hurles *et al.* [1978] for the detection of deep level trapping centres in semi-insulating GaAs, and further applied by Yuba et al. [1982, 1983] to both GaAs and InP. Essentially, the technique involves the periodic filling of trapping centres by carriers generated by pulsed laser light followed by rate analysis of the exponentially decaying, thermally stimulated, trap-emptying transient currents as the sample temperature is slowly ramped.

Unfortunately, unlike the DLTCS method, the OTCS technique cannot provide information on whether the trap is electron or hole trapping. Also, owing to factors which prevent complete trap-filling or more particularly, the non-uniform filling of traps due to non-uniform light absorption in the sample, the capture cross sections and concentrations of traps are not easily estimated. However, in many instances, knowledge of the trap activation energy E_T alone is very useful and the comparative simplicity of the OTCS method is attractive.

A requirement of the OTCS system is the need to use ohmic contacts, but this can introduce serious problems, such as unwanted defect annealing and other material changes, which can be associated with the high processing temperatures often needed for ohmic contact formation.

A transient a.c. conductance method for the analysis of deep level traps in high resistivity semiconductors has been developed. The novelty of this technique is that it eliminates the need for ohmic contacts, replacing them with the lossy dielectric of a capacitor which is connected across the tank circuit of a simple radiofrequency ($\sim$ 40 MHz) marginal oscillator detector (MOD). A description of the principles and practical operation of the spectrometer system is given and measurements of spectra from compensated, In-doped CdTe are presented.

2. PRINCIPLES OF THE OPTICAL TRANSIENT SPECTROMETER SYSTEM

2.1 Basic Theory of Trap-controlled Photoconduction in Semiconductors

To understand the origin and waveform of the signal generated by the MOD output, it is first necessary to review briefly the theory of the electronic processes governing the optically stimulated carrier-trapping and emission (see Bube [1960] for a general account of trapping processes in photoconductors).

The emission rate, e, of a carrier trapped on a centre with activation energy or trap depth, E_T, from the appropriate band edge is given by the relation

$$e = 1/\tau = \frac{\sigma \upsilon N}{g} exp - (E_T/kT) \quad , \tag{1}$$

where e is the carrier emission rate from the trap, τ is the trap decay time constant, σ is the capture cross section of the trap for carriers, N is the density of states in the band at temperature T, υ is the average thermal velocity of carriers at T, g is the degeneracy of the trap, and k is the Boltzmann's constant.

Equation (1) can be re-written as

$$log_n \ \tau = constant + (E_T/kT) \tag{2}$$

from which, with suitable temperature corrections [Miller *et al.* 1977], experimentally measured values of E_T may be obtained.

Further, if n_T is the number of trapped carriers, the rate of change of trapped carriers will be given by

$$dn_T/dt = - n_T e \quad . \tag{3}$$

The solution of this equation is

$$n_T = n_{To} exp (-et) \tag{4}$$

where n_{To} is the number of initially trapped carriers following a pulse of light. If the carriers recombine in a time τ_R, which is short compared to the period of emission, the variation in concentration of excess free carriers Δn will be given as

$$\Delta n = \frac{-dn_T}{dt}\tau_R \quad , \tag{5}$$

or

$$\Delta n = n_{To}\,\tau_R\; e\; exp(-et) \quad . \tag{6}$$

Thus, the photo-induced trap-emitting conductance of the sample will decay exponentially in time with a period 1/e for the condition stated; by using an exponential correlator [Miller *et al.* 1977], it is possible to measure directly the trap emission rate e from the sample transient conductance at any temperature. It is important to note that the use of the Miller correlator for detection of a transient signal of the form given by Equation (6), because of the presence of the emission rate factor e, requires recalculation of the correlator response function as given earlier by Miller *et al.* [1975].

2.2 Approximated Equivalent Electrical Circuit of a Capacitively Coupled, Semi-insulating Sample with Photoconductive Losses

To appreciate the MOD method of conductance measurement, consider the equivalent circuit of a capacitively coupled, semi-insulating photo-illuminated sample shown schematically in Figure 1(a). The sample is illuminated by pulsed, short wavelength light ($h\upsilon > Eg$) at one contact which is a thin, semi-transparent, metal-coated dielectric sheet (in practice Mylar foil is used) in contact with the surface of the sample. If it is assumed quite simply that the photoconducting lossy region is confined to layer A (ignoring the spatially non-uniform generation of carriers due to stronger absorption of light at the surface), the equivalent circuit of the sample can be approximated to that shown in Figure 1(b), where R_p represents the time variable, photo-induced trap-controlled resistance of layer A in parallel with the capacitor, C_A represents the capacitance of the layer shunted by a dark resistance R_A; C_B and R_B are, respectively, the capacitance and dark resistance components of the un-illuminated part of the sample.

Simplifying this further, assume that $R_p << R_A < R_B$ and R_p is much less than the capacitive reactance of C_A; the equivalent circuit can then be further approximated to that of Figure 1(c), where C_D is the resultant series combination of the contact and non-illuminated layer B capacitances. Thus the equivalent sample circuit seen by the tank circuit of the marginal oscillator is that of a variable resistor R_p in series with a capacitor C_D, the value of which, in practice, is determined largely by the geometric capacitance of the non-illuminated layer B. (It should be kept in mind that the equivalent circuit shown in Figure 1(c) converts to that in Figure 1(b) with time as the value of R_p increases with trap decay.) Additionally, if the capacitive reactance of C_D at the oscillator frequency of 40 MHz is much less than R_p (for example, $X_{C_D} = 400\ \Omega$ for a 1 cm^2 area, 1 mm thick section of semi-insulating material with a dielectric constant of 12; R_B may be $> 10^4\ \Omega$) then the lossy, photoconductive induced resistance R_p (or its conductance G_p) will appear across the marginal oscillator tank coil.

2.3 Response of Marginal Oscillator to Transient Photoconducting Load

In essence, the marginal oscillator converts small changes in the tank or tuned circuit resistance into a change in amplitude of the oscillation. This may be brought about by enveloping the sample with the tank coil, as in nuclear magnetic resonance (NMR) spectroscopy, or by placing a shunt conductance, in the form of a parallel plate cell containing gaseous ions, across the resonant circuit as in ion cyclotron resonance (ICR) measurements; obviously, the effect of a lossy conductance in a photoconductor may be similarly detected by placing the device in shunt with the oscillator tank coil.

Although it would be very useful to derive an analytic expression for the signal developed across the oscillator resonant circuit in response to a transient photoconducting load to predict detector sensitivity and linearity, this is impossible for the simple positive feedback oscillator described here, owing to the unknown, highly non-linear loop feedback characteristic featured by the oscillator. Thus measurement of the detector response characteristics must be accomplished by electronic means (see Section 3.1 for further discussion). It is worth noting that this problem does not occur in the case of the 'limited self-oscillator' circuit described by Robinson [1959] for which a simple, closed expression for the resonant circuit voltage can be derived in terms of added shunt conductance.

3. SPECTROMETER SYSTEM WITH MARGINAL OSCILLATOR DETECTOR

3.1 Practical MOD System

The DLT spectrometer system with a marginal oscillator detector is shown in Figure 2. The semi-insulating sample of material, clamped between Mylar dielectric capacitive contacts, is mounted in a vacuum crystal cooled by liquid nitrogen. The temperature of the sample is monitored by a copper/constantan thermocouple (T), the output of which is fed into an X-Y recorder. A type SG3001

stacked-diode GeAs laser is used to illuminate the upper, exposed contact via a light guide. Typically, the laser is operated at a peak average power of 80 W with a pulse duration of $\cong$ 1.0 μs, and is triggered by the Miller correlator.

As mentioned previously, marginal oscillators have been widely developed, especially for application in the detection of low-level nuclear magnetic and ion cyclotron resonance signals. The development by Robinson [1959] of an amplitude-limiting oscillator having low noise and stable characteristics is of particular note as most later designs have been based on that principle [McIver 1973; Warnick *et al.* 1974]. However, several MOD circuits using simple single or dual stage oscillators have also been described, mostly using field effect transistors as low noise, positive feedback amplifiers [Idoine and Brandenberger 1971; Yagi *et al.* 1973; Rahf 1981]. For this work, we chose to use the modified Franklin oscillator design described by Idoine and Brandenberger [1971] and shown in Figure 3.

Inductor L_1 and variable capacitor C_1 are the essential components of the parallel resonant oscillator tank circuit (resonant frequency $\sim$ 40 MHz); L_2 and C_2 limit the passage of lower frequencies (e.g. microphonic signals) directly through the first stage field effect transistor (FET), F_1, of the oscillator. Demodulation of the radiofrequency signal occurs at the drain of F_1 by a process similar to 'plate detection'; the signal is then passed via the radiofrequency filter capacitor C_3 through a coupling capacitor C_4 to a buffer amplifier. The circuit shown in Figure 2 is a modification of the original to increase the pass band of the coupling components, C_4 and R_3, at low frequencies so as to accommodate demodulated photoconducting decay signals with periods up to $\sim$ 100 ms. The demodulated signals are then processed by the Miller [1977] exponential correlator-integrator unit, the output signal from which is fed into the X-Y recorder. The marginal oscillator components were solidly mounted and well shielded, and particular care was taken to use a stable, low-ripple supply to F_1 and F_2.

To obtain an estimate of the sensitivity of the marginal oscillator radiofrequency output voltage as a function of shunt resistance across the tank circuit, the output was plotted for various loading resistors, R_L, at constant d.c. potential at the common sources of F_1 and F_2 (Figure 3). These static characteristics are useful for by observing the magnitude of the decrement in the oscillator radiofrequency output during a photoconducting pulse decay signal, an estimate of the equivalent shunting resistance of the sample can be made. However, as can be seen from the relative insensitivity of the marginal oscillator radiofrequency output to R_L values beyond $\sim$ 5 KΩ this characteristic has limited application.

More appropriate would be the use of a dynamic 'Q spoiler' of the type described by Adler *et al.* [1971], in which the radiofrequency conductance of a transistor connected to a common base and applied in shunt across the oscillator tank circuit can be modulated by a current through the emitter-base diode. Alternatively, although possibly less flexible in approach, the sensitivity test circuit described by Warnick *et al.* [1974], in which an FET is used to switch resistance electronically across the tank circuit, could be used. In both calibration systems, a more direct measure of sensitivity could be obtained by observing, as it appears on the oscillator radiofrequency output, the demodulated amplified conductance signal rather than the low-level modulating conductance signal which is difficult to measure. In addition, by using the first of these calibrators, it should be possible to simulate an exponentially decaying conductance load and detect the signal synchronously with the Miller correlator, giving the sensitivity of the overall MOD system.

In operation, the optimum conditions for marginal oscillator detection were determined by observing the photo-decay signal and maximising it by adjusting VR_1. In practice, this adjustment is not very critical. Figure 4 shows a typical trap-emission signal from a sample of semi-insulating cadmium telluride taken at the buffer amplifier output of the MOD. The initial spike represents the photoconducting signal generated during and immediately after the laser pulse of excess electrons and holes. The response time of the MOD was measured at < 5 μs.

3.2 Deep Level Transient Conductance Spectroscopy of Semi-insulating CdTe

The feasibility of the MOD as a DLTCS detector was examined using semi-insulating GaAs and CdTe samples, equivalent results being obtained from both materials. Results are given here for CdTe only. Figure 5 shows a typical spectrum of deep traps recorded from a sample of In-doped, semi-insulating (bulk resistivity $> 10^9$ Ω cm) Bridgman-grown CdTe taken with a correlator time constant of 6 ms. The optimum signal amplitude was determined by adjusting V_{R1} of the marginal oscillator; the voltages labelling each spectrum of Figure 5 correspond to the d.c. level at the common source connection of F_1, F_2 of the oscillator. For this particular sample, background spectral noise was negligible.

4. DISCUSSION

It has been shown that a simple marginal oscillator can be used as a transient conductance detector in the deep level trap spectroscopy of semi-insulators which cannot be investigated by the DLTCS technique. The response time of the detector is fast and although a precise measurement of the sensitivity of the oscillator in terms of trap or photocarrier densities was not made, there is evidence that the sensitivity will permit practical measurements of trap energy levels using simple capacitive coupling to samples, thus eliminating the requirement for ohmic contacts. A first order theory involving an approximated equivalent circuit of the photoconductor shows that, at least for low conductance loading, the oscillator output varies linearly with photocarrier density.

By way of an example, when the method was applied to the measurement of deep traps in In-doped, semi-insulating CdTe (AAEC Bridgman-grown crystal), three deep level traps were located; the E_T values for two of these levels agreed with values reported elsewhere.

Although details are not given, the MOD system has been used at these laboratories to record deep level spectra from γ-irradiation induced defects in Ge and gold-related levels in Si. Both samples had ohmic contacts, and were not from dose-compensated, high resistivity material. This shows that a wider conductivity range of semiconductor can be analysed, the only restriction being that the sample resistance should not be so low that it quenches the oscillator.

It should be noted that the MOD conductance mode does not require high electric fields, as is often the case in DLTCS, therefore the possibility of complicating Poole-Frenkel (field-sensitive emission) effects on the measurement of trap activation energy is diminished. Further, the use of high frequency oscillators (~ 40 MHz compared with 1 MHz in the common commercial capacitance bridges used for DLTCS) enables the measurement of the deep levels at higher scanning temperatures (higher emission rates) thus avoiding freeze-out of the shallow background levels at low temperatures, an effect which limits the usefulness of DLTCS [Kimerling *et al.* 1981].

One disadvantage of the MOD spectrometer is its inability to provide a direct measure of trap concentration, unlike DLTCS. Because little is known about the lack of knowledge of the primary photocarrier concentration, the diffusion kinetics of carriers, and the non-linear generation of carriers with depth because of light absorption, an exact physical description of the trap-controlled conducting layer of the sample is lacking. In addition, the amplitude of the conductance signal is also determined by the carrier recombination lifetime (Equation (5)) which is also an unknown quantity. Despite these drawbacks, in many investigations the variation in relative trap concentrations can be very useful (annealing experiments, for example).

Although trap concentrations may not be measurable, trapping cross sections can be estimated by measuring the pre-factor in Equation (1) (intercept on emission axis for $1/T \fallingdotseq 0$).

Further development of the MOD transient conductance deep level spectrometer will be directed towards the use of higher frequency oscillators using high Q tank circuits, possibly of the tuned cavity type. The Robinson amplitude limited oscillator has the advantages of lower noise and greater insensitivity to microphonics than the simpler oscillator reported here; they should be investigated together, using an electronically variable conductance calibrator for sensitivity determination.

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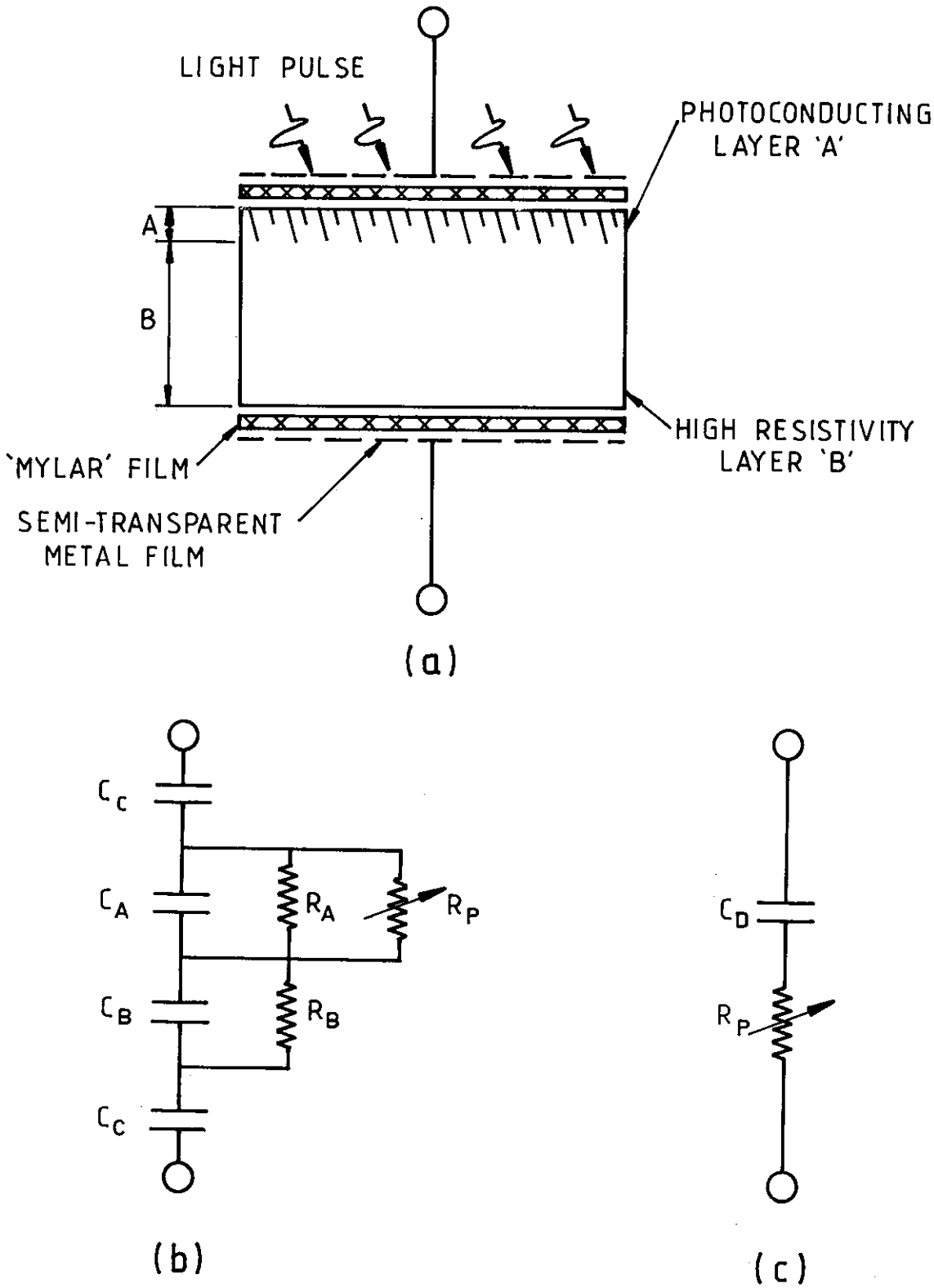


FIGURE 1 (a) Schematic outline of a high-resistivity semiconductor sample with semi-transparent capacitive contacts illuminated by pulsed, short wavelength light ($h\upsilon > Eg$). (b) Equivalent circuit showing the time-variable (trap-dependent) resistive component R_p generated in the photoconducting layer 'A' close to the illuminated contact. (c) Simplified equivalent circuit for the case of a highly photoconducting layer 'A': $R_p \ll R_A < R_B$, where R_A, R_B are the quiescent resistances of layers 'A' and 'B' respectively; C_D ($= C_B\, C_C/(2C_B + C_C)$ is the resultant series combination of the contact and 'B' (non-photoconducting) layer capacitances.

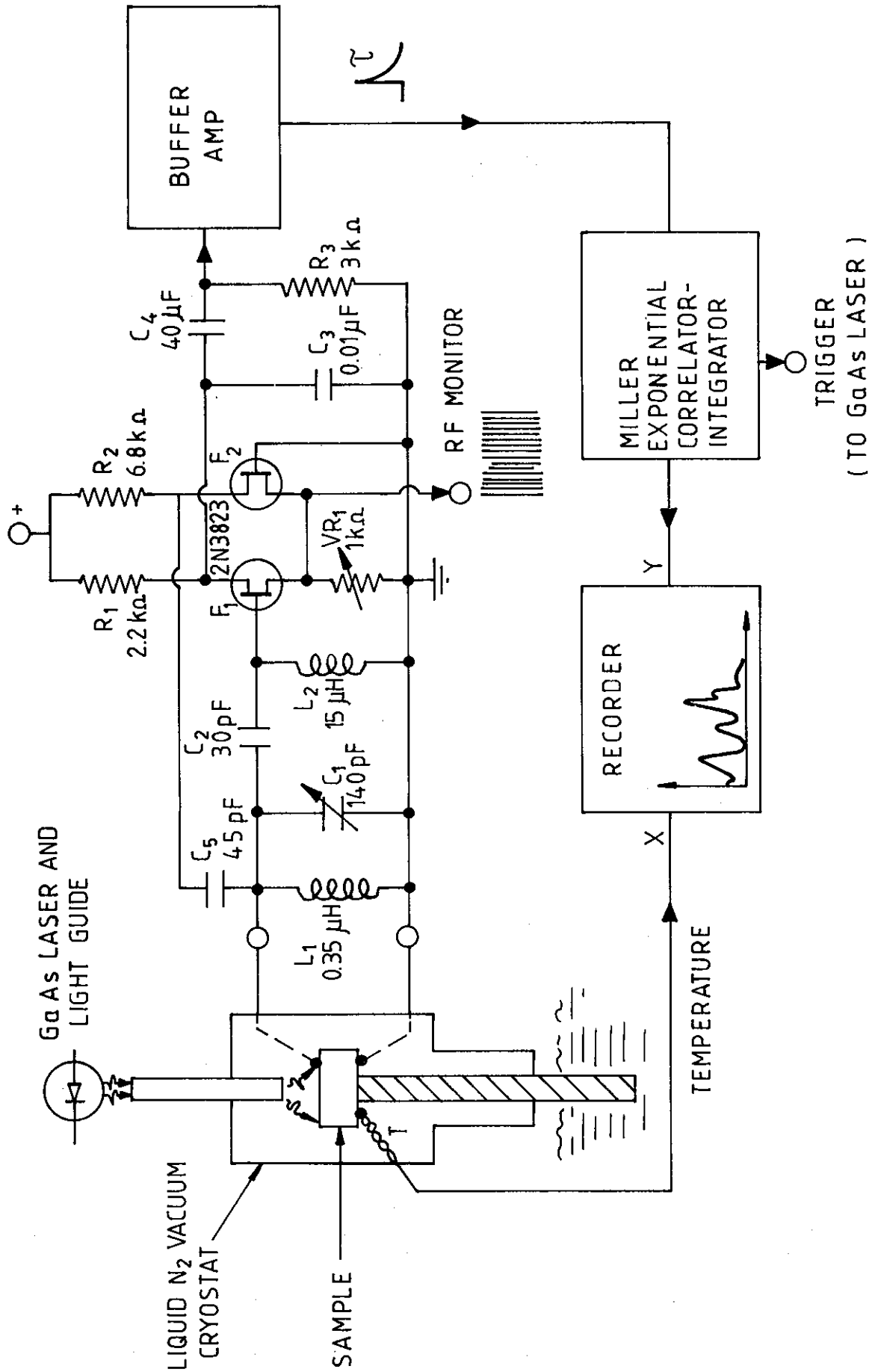


FIGURE 2 Schematic of overall DLT spectrometer system using a marginal oscillator detector.

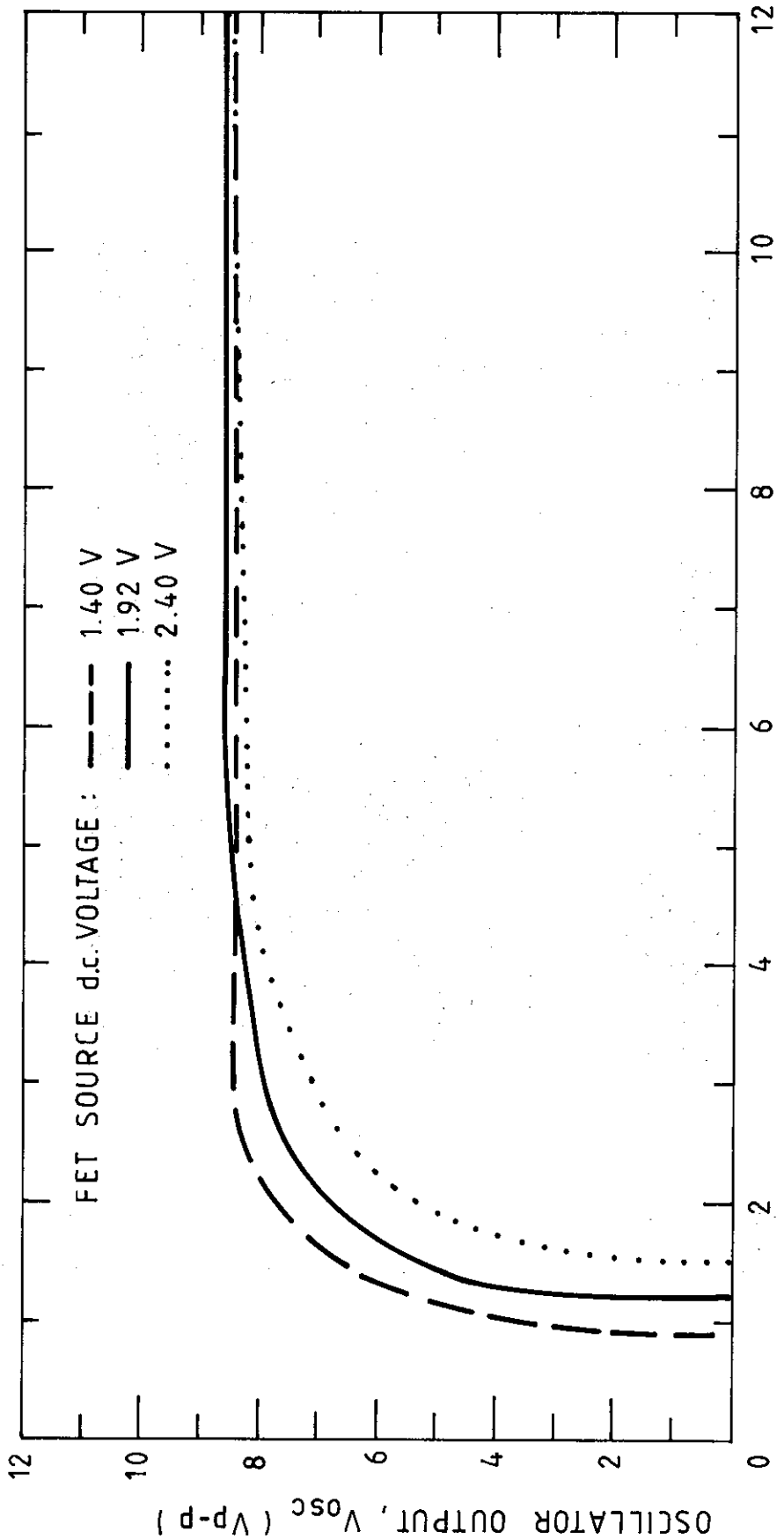
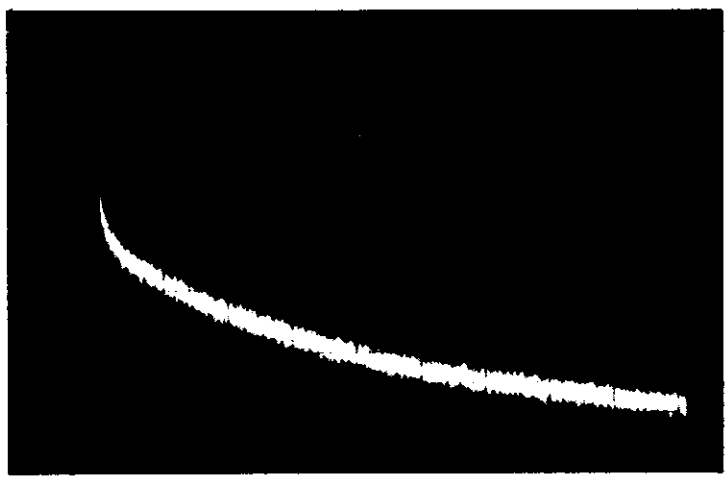


FIGURE 3 Radiofrequency output of marginal oscillator as a function of shunt tank load resistance.

(a)



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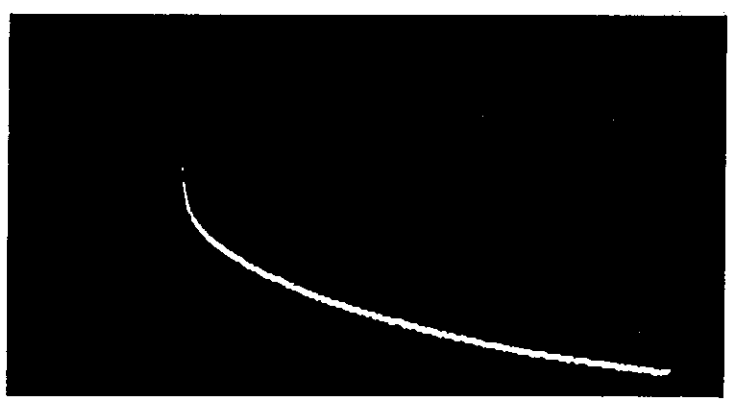

FIGURE 4 (a) Marginal oscillator detector transient conductance signal from trap emission in a sample of semi-insulating CdTe (trap $E_T = 0.58$ eV of Figure 5). Standard oscilloscope viewing; 0.1 V cm^{-1}; 1 ms cm^{-1} sweep speed. (b) Storage oscilloscope, viewing 256 sweeps; 0.1 V cm^{-1}; 2 ms cm^{-1} sweep speed.

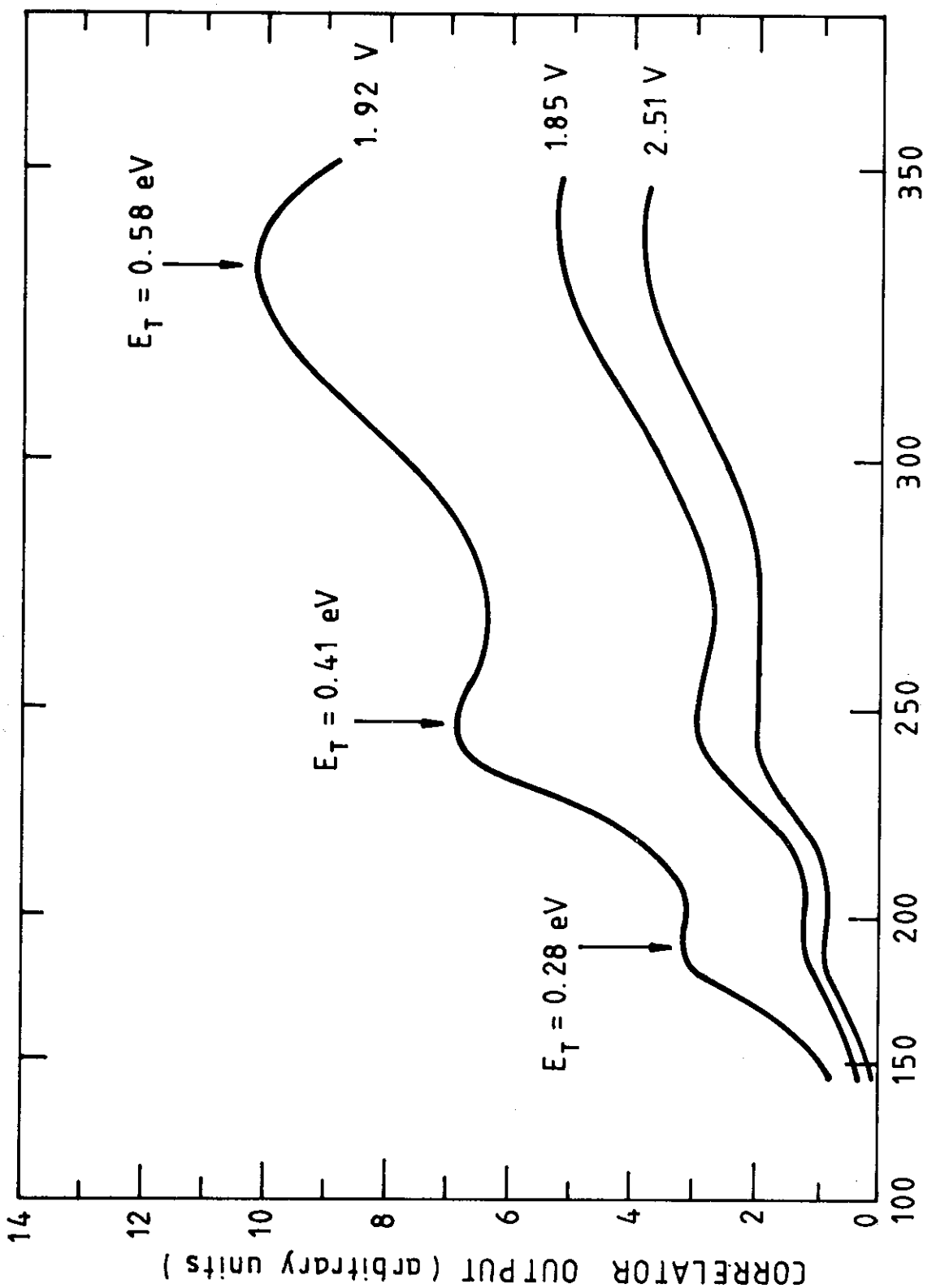

FIGURE 5 Deep level transient conductance spectra from a sample of semi-insulating CdTe using the marginal oscillator detector (correlator time constant = 6 ms).