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ABSTRACT

This document serves as an introduction to the various forms of space-charge spectroscopy of deep levels in semiconductor junctions and contains operating instructions for the present DLTS system.
Contents

1. Introduction
2. Experimental
3. Space-Charge Spectroscopy
   3.1 Capacitance DLTS
   3.2 Current DLTS
   3.3 Charge Transient Spectroscopy
   3.4 Conductance Transient Spectroscopy
   3.5 Constant Capacitance DLTS
   3.6 RDLTS
   3.7 Admittance Spectroscopy
   3.8 DLOS
   3.9 RC Time Constant Problems
4. Operation of DLTS System
   4.1 CTI Cryostat
   4.2 Janis Dewar
   4.3 Correlator
5. Collection of Data
   5.1 Trap Activation Energy
   5.2 Trap Cross Section
   5.3 Trap Concentration
   5.4 Capacitance-Temperature Measurements
6. Calculation of Defect Parameters
   6.1 Energy Level
   6.2 Cross-Sections
   6.3 Concentration Profiles
   6.4 Net Doping Density
   6.5 Current-Temperature Dependence
   6.6 Forward Bias Pulsing, LED Injection
7. Miller Profiler
8. High Trap Concentrations
9. Poole-Frenkel Effect, Recombination-Enhanced Annealing
10. Miscellaneous
    10.1 Alloy Broadening of Levels
    10.2 DLTS Uniaxial Stress Experiments
    10.3 Near Surface Concentration Profiles
1. INTRODUCTION

The spectroscopy of deep level centers in semiconductors is a relatively new area, and although the experimental techniques involved are now standard in many laboratories, a true understanding of the microscopic nature of the centers themselves is generally lacking. A number of techniques relying on the modulation of the depletion depth at a p-n junction yield the activation energy, capture cross-section for electrons and holes, the concentration profile and the donor or acceptor nature of the deep level center, but these space-charge spectroscopy methods do not give information on the structure of flaws in the semiconductor lattice. One method of relating measurements from the spectroscopic techniques with the structure-revealing techniques such as electron spin resonance is discussed in section 10.2 of this paper. In many cases, one is not even interested in the microstructure of a particular deep level center, but rather its chemical origin, so that steps can be taken to eliminate the impurity from subsequent samples, or at least identify that same level if it is found in other samples.

Deep levels often result from complexes of impurities and intrinsic defects, which makes their microstructure difficult to understand. The theoretical treatment of deep levels is also in principle difficult because of this complexing and because of strong electron-phonon interactions. This lattice coupling implies strong localization of the defect in real space, and hence an extended nature in momentum space. It also means that most deep states are non-radiative. The assumptions of effective-mass theory do not hold for deep level centers, and a number of approaches have been used to obtain theoretical predictions for the electronic parameters of such levels [1,2].
In this paper we will describe a number of the space-charge spectroscopy techniques for detecting deep level states in semiconductor junctions, and in particular, detail the use of the present deep-level transient spectroscopy (DLTS) system.

2. **EXPERIMENTAL**

Samples for the most commonly used space-charge techniques are prepared by forming p-n junctions or Schottky diodes out of the sample material. Table 1 lists suitable contacts for Si, GaAs, GaP and Ge; Table 2 lists suitable etchants for these materials. Samples should typically be of the order of 5 x 5 x 3 mm$^3$; the actual size can vary within the constraints of the availability and purity of the material (remember the capacitance meter reads only to 3000 pF) and the RC time constant associated with the capacitance of the depleted material, and the resistance of the undepleted material. The RC product must be less than $(2\pi f)^{-1}$, where $f = 1$ MHz is the measurement frequency of the bridge, i.e. $RC < 1.6 \times 10^{-7}$ s. In general, only large, pure samples give problems. Use of a lower measurement frequency, such as with a lock-in amplifier, can help alleviate some of the RC problems. One must also remember that for capacitance transient measurements, the capacitance of the device must in general change with reverse bias—otherwise no synchronous emptying and filling of the deep level trapping centers is possible using a bias pulse.

The samples must be prepared to a reasonably high standard. Nonfastidious etching or handling will result in excess leakage current which may upset the phase-sensitive detection circuitry in the capacitance meter. Surface states may also produce a DLTS response, especially when forward bias pulsing or light emitting diode injection of minority carriers is used. A high reverse leakage current can also disturb the occupation statistics of deep levels by
providing an uncontrolled source of minority carriers. Use of bias pulses of various amplitudes as described in section 6.3 enables the concentration profile of deep level electron or hole traps to be obtained, though this is tedious. Cleanliness where the samples are concerned is advisable to reduce contamination problems. The actual leakage current above which the capacitance bridge is affected is a function of the capacitance of the sample, but generally adjustment of the standing reverse bias so that the reverse leakage current is of the order of $\mu$A or less will suffice. Germanium samples of course must be cooled to the extrinsic temperature region ($< 200$ K) before DLTS spectra can be recorded. At room temperature "intrinsic" Ge samples have considerable thermally excited leakage current (several mA at a few volts).

Standard samples for capacitance spectroscopy may be p-type Ge with Cu or $^{60}$Co $\gamma$-ray damage, Au diffused n- or p-type Si, or n-type Si (irradiated) with $^{60}$Co $\gamma$-rays. Table 3 describes the conditions under which these standards can be prepared, and Figures 1-5 show the standard spectra obtained under typical DLTS running conditions.

3. SPACE-CHARGE SPECTROSCOPY TECHNIQUES

The most commonly used technique is of course DLTS. The standard review articles deal with the background, applications and instrumentation used [3,4]. In essence, one measures repetitive, thermally activated capacitance transients of a given time constant. The rate of decay or recovery of capacitance transients caused by the emission of trapped electrons or holes is matched to a standard recovery waveform, which forms a rate window. The output of the electronic processing instrumentation is a maximum when the experimental transient falls within the rate window selected. A number of signal processing schemes are possible, including use of a boxcar integrator, lock-in amplifier or correlator [3].
3.1 Capacitance DLTS. The principle of the DLTS technique depends on two phenomena. First, the variation of the test p-n junction capacitance with the applied reverse bias (Fig. 6), and second, the capture and emission of free charge carriers by defect centers within the diode depletion region. A localized defect level can alter the space charge density by this carrier trapping, causing a change in depletion depth and thus capacitance. In the DLTS measurement, the applied reverse bias is periodically reduced, filling the localized defect levels. As the trapped carriers are thermally re-emitted, the time dependence of the capacitance is measured by a high sensitivity, fast transient response bridge (Fig. 7). The DLTS technique uses the fact that each defect state possesses a unique energy level and capture cross section, which enables a spectroscopic display of the defects present in the depletion region.

The transient capacitance signal is processed so that a selected decay rate produces a maximum output. As the temperature of the test sample is scanned, changing the emission rate of the defect level, a spectrum peak in the signal output versus temperature data occurs when the capacitance recovery rate passes through the preset rate window. For our system, a Miller correlator is used. This instrument generates an exponential waveform whose decay rate may be externally generated (1 - 100 ms). This exponential waveform and the exponential capacitance recovery waveform due to discharging of the defects in the test sample are multiplied, and the resulting signal is integrated to give a DC output. A DLTS peak is achieved when the two rates are equal—changing the pre-selected decay rate means the temperature at which the two rates are identical also changes, and this temperature dependence gives the activation energy for carrier emission from the particular defect level to the appropriate band (Fig. 8). The calculation, and methods of measuring the defect parameters are detailed in sections 5 and 6.
3.2 Current DLTS. A number of schemes have been devised to measure the transient current resulting from carrier capture and emission in a test p-n junction sample [5,6]. The essential difference from capacitance DLTS is that an electrometer or high gain current amplifier is used in place of a capacitance meter. The disadvantage of such techniques is that the current transients are all of one sign, whereas the sign of a capacitance transient depends on the sign of the trapped charge. Thus one is in principle unable to determine the type of trap giving rise to the current transient. These measurements are also subject to interference from standing diode leakage currents, thermoelectric currents and secondary photocurrents. The spatial variation of sensitivity for current transients is a maximum at the sample surface, and falls linearly to zero at the back of the depletion region, the opposite of the capacitance transient case. This is another method of determining surface state effects. Peaks achieved in current DLTS or TSC which do not appear in capacitance DLTS or TSCAP are most likely due to surface states.

The sensitivity of capacitance DLTS is independent of the time constant of the capacitance transient whereas the sensitivity of current DLTS is directly proportional to the rate of the current transient. Thus current DLTS measurements are most sensitive for fast transients, while capacitance DLTS is most sensitive for slow transients. The cross-over point where both methods have similar sensitivity is for time constants of order 1 - 10 ms. Current transient spectroscopy is useful for measuring semi-deep centers whose energy levels lie near the primary dopant for two reasons. Firstly, premature freeze-out effects associated with the bridge measurement frequency are avoided, and secondly if one can use a high carrier emission rate, which is more easily measured using current transients, then closely-spaced defect peaks are more easily resolved.
3.3 Charge Transient Spectroscopy. This method relies on integrating the current transient from the sample and thus retains the high speed advantage of current DLTS, but avoids the loss of sensitivity with decreasing thermal emission rate [7]. A wide range of time constants can be measured with high sensitivity, and the integrating circuit is quite simple, consisting of a high speed FET OP amp with parallel RC feedback loop.

3.4 Conductance Transient Spectroscopy. The fundamental limit to the sensitivity of capacitance DLTS is reached for semi-insulating devices, or for those in which the capacitance change with bias is very small. In this case, one may monitor the transient conductance of an ohmic device by a simple modification to a standard capacitance meter. To convert to the conductance mode, the sample RF signal voltage into the phase detector of the bridge is interrupted, and the phase of the signal shifted $270^\circ$ to enable observation of the real component of device impedance. This can be effected using a delay amplifier, with a calibrated coaxial cable acting as a phase trimmer. The phase is optimized by noting the maximum response when a resistor is placed across the test terminals of the capacitance meter (or alternatively, a null response if a capacitance is added). Pulsed band-edge illumination is used to disturb the equilibrium population of deep level centers, while a slightly longer bias pulse sweeps out excess carriers [8]. Such a system is very useful for small area devices such as field effect transistors.

3.5 Constant-Capacitance DLTS. In the constant capacitance mode, the depletion width is held constant by dynamically varying the applied voltage during the transient response, permitting more accurate measurements of defect profiles when the trap concentrations are high. The usual DLTS relations are derived in the low concentration limit:
\[ \frac{\Delta C}{C} \quad \text{or} \quad \frac{N_T}{N_D-N_A} < 0.1 \]

In the high concentration regime the depletion width changes during the transient response to a charging pulse, and the above approximations are no longer valid. These problems may be circumvented by employing the constant capacitance mode [9]. In this case one matches the decay rate of the transient voltage needed to keep the diode capacitance constant. To ensure that the electric field present in the depletion region does not upset the measurements, a further modification, double-correlation DLTS [10] may be used. A narrow spatial interval is defined in the depletion region by using a dual-pulse generator to apply pairs of voltage pulses, with the adjacent pulses set at different amplitudes, and separate signal integrators are used to record the DLTS signal for each pulse in the pair.

A method for converting a Boonton 72B* capacitance meter to the constant capacitance mode has been described by Li and Sah [11]. Although in principle this conversion is simple, in practice it is difficult to implement without extensive adjustment of circuit parameters.

3.6 RDLTS. In this method, a reverse bias pulse rather than a zero (or forward) bias pulse is applied on top of the reverse DC bias. When the pulse is removed, a capture transient signal is obtained, rather than an emission transient. The rate is measured as in conventional DLTS. Effectively one obtains the normal DLTS spectrum, with the sign of the peaks inverted. The capture of carriers takes place in a narrow region of the depletion region, and to obtain adequate sensitivity the pulse width is typically a hundred times longer than a conventional filling pulse. The electric field in the region of interest can be closely controlled, and the technique has

*See Acknowledgments.
application to the measurement of electric field enhancement of carrier emission rates [12].

3.7 **Admittance Spectroscopy.** This involves the low frequency measurement of the capacitive and conductive components of the junction admittance at two or more frequencies, as a function of temperature. A lock-in amplifier detects the phase of the currents resulting from thermal emission of trapped carriers within the sample diode. The bias voltage on the sample is thus sinusoidally varying. As the temperature of the sample is scanned, the emission rate of trapped carriers changes until they are able to follow the driving voltage, leading to a step in the sample capacitance and a peak in the AC conductance response of the sample [13]. The technique is complementary to DLTS in that it is better suited to p-i-n samples where normal bias pulses are ineffective in filling the defect levels.

3.8 **Deep Level Optical Spectroscopy.** As well as using bias pulses to fill deep levels, one may of course use "optical" filling. One variant, DLOS, is based on photostimulated capacitance transient measurements after electrical, thermal or optical excitation of the sample diode. The complementary use of normal DLTS allows both the optical and thermal properties of defects to be investigated. The various electrical or optical pulsing sequences for the DLOS modes of DLTS are shown in Fig. 9 [14]. One advantage of DLOS is that it enables measurement of the spectral distribution of the optical cross sections for transitions between a deep level and either of the bands; this is a good test of many theoretical models of deep defects.

3.9 **RC Time Constant Problems.** The effects of the RC time constant of the sample were briefly discussed in section 2. One may experimentally verify
that there is a problem by adding a resistance in series with the sample, and observing the effect on the sign of the various peaks in the DLTS spectrum of the sample. As the series resistance is increased, the peaks will invert, as discussed by Broniatowski, et al. [15]. If no sign reversal is observed, then one may conclude that the sign of the transient was reversed from the start due to an RC problem with the sample itself. A method is given in reference [15] for correcting DLTS spectra for the effects of series resistance.

4. OPERATION OF DLTS SYSTEM

DLTS samples of the type described in section 2 may be thermally scanned in either the cryostat cooled by a CTI model 21* closed cycle refrigerator, or the Janis model DT* helium gas exchange dewar.

4.1 CTI Cryostat. To load the sample one backfills either system with He gas, and removes the dewar insert, or the top hat and reflection shields depending on the choice of cryostat. Both have similar sample mounting arrangements—the sample is placed n+ side up on the In pad which acts as one electrode. In this configuration both the bias and bias pulse should have positive polarity. A small pad of In is placed on the n+ contact, and the wire acting as the top electrode is clamped on top of the In using the adjustable tension spring with the teflon plug on it. For Li n+ contacts it is advisable to rub on some GaIn to provide a low resistance contact to the n+ contact itself. A visual check for short circuits is made and one should make sure that the diode is not too firmly clamped in place. As the sample is cooled, vibration of the top contact wire may produce excess noise, particularly in the closed cycle refrigerator cryostat, which has the problem of vibrations from the compressor action.

One or two volts should be applied to the sample at room temperature to check the leakage current, to ensure that the capacitance decreases with bias,
and also to check for shorts in the system. This may be achieved by switching the polarity of the applied bias and checking that the leakage current in the forward direction is substantially higher than in the reverse direction. Switches on the front of the bias supply enable one to read the applied bias and leakage current on a multimeter to the right of the capacitance bridge. Leakage currents > 15 mA will blow either of the fuses in the Boonton 72B meter. If after testing the sample leakage current the capacitance does not respond to changes in bias, or does not show a transient on application of the bias pulse, the two fuses can be checked by pulling the bridge forward and removing them.

The reflection shields and top hat should be replaced, or the dewar insert replaced, and the system evacuated in the normal manner. Cooling of the cryostat system is straightforward—the compressor is switched on, allowed to run for approximately one minute, then the cold head is started. The sample will start to cool, and should reach ~ 20 K within ~ 90 min. To heat the sample, the compressor and cold head are turned off, and current is passed through the heater wound below the sample platform within the cryostat. If one wishes to heat the sample in vacuum, the current should be limited to ~ 400 mA. To achieve faster heating, the cryostat is isolated from the diffusion pump and backfilled with He gas; one may then apply up to 800 mA of heater current. Caution should be taken with this procedure at low temperatures, as the sample will warm very quickly, and this introduces a hysteresis error in the position of low temperature peaks. Do not leave the system unattended while heating up because overheating can cause damage.

4.2 Janis Dewar. The cooling of samples in the Janis dewar is a more complicated procedure. Figures 10a and 10b show schematics of the dewar. The sample space should first be thoroughly evacuated, and alternately backfilled
with He gas and evacuated to ensure no water remains at the bottom of the space. While pumping on the sample space one should open the He needle control valve several turns, and listen for the gurgle of the pump. This means the valve is clear, and one should never try transferring LHe if the valve is not initially clear. The thermal isolation space is then evacuated to ~30 μm, and the LN$_2$ space filled. The vacuum in the isolation space should drop dramatically. After purging with He gas, the LHe reservoir should be pre-cooled by filling with LN$_2$. Once full, the LN$_2$ is blown out by forcing He gas into the space, making sure that all the LN$_2$ in the reservoir is removed. Flushing with He gas should continue for at least five minutes after the last drop of liquid is removed.

Liquid helium should be transferred in the normal manner using the large transfer tube. The isolation space of the transfer tube should be evacuated and the tube itself flushed with He gas. The transfer takes ~25 min at a transfer pressure of ~1 psi. A He line from a cylinder in the corner of the room is available to pressurize the LHe dewar, and all other appropriate attachments to the Janis dewar are on the tray at the bottom of its support trolley. During transfer the helium needle control valve on the Janis should be opened several times, and one should check for the gurgle of the pump to make sure the valve is clear. The Janis operating manual gives more details. Once transfer is complete, the tube should be withdrawn slowly, the LHe dewar capped, and the blow-off valve placed on the vent pipe of the He space on the Janis dewar. A small metal plug and O ring seal the filling pipe on the He space. The sample space should be backfilled with He gas, and the dewar left to sit for ~30 min. This allows the LHe to collect at the bottom of the sample tube, but more importantly it allows the walls of the sample space, and the copper block on which the sample is mounted to cool down. Failure to allow this to happen greatly increases the amount of LHe required to cycle the sample.
The dewar will cool by this method to ~ 200 K. The sample space should then be continuously evacuated, and the He needle control valve opened several turns while applying ~ 50 mA of current to the He vaporizer. Cold He gas is thus pumped past the sample, cooling it down. The pump or He control valve can be throttled to maintain the lowest equilibrium pressure in the sample space. If the pressure is too high the sample will cool much too slowly, wasting LHe. On reaching 4 K the needle valve is closed, the vaporizer current and pump turned off, and current applied to the sample heater to begin the upward temperature scan. At low temperatures a heater current of 100 mA is appropriate; at higher temperatures (> 50 K) currents up to 800 mA can be applied. Fuses in both the vaporizer and heater current meters protect against excess voltage application. Stabilization of the temperature at any required value is possible using the Lakeshore cryogenic temperature controller which is normally connected to the Hall effect system. Connections to the Janus are available on the meter box displaying the vaporizer and heater currents.

To remove the sample, the gas should be blown into the sample space, preventing air from condensing in the space when the insert is removed. Typically between 8 - 12 samples can be scanned on the 8 l capacity of the dewar, taking into account that two samples can be loaded at a time.

4.3 Correlator. A block diagram of the correlator is shown in Fig. 20. The experimental transient is multiplied by a decaying exponential (weighting function) and integrated to give a DC output. This is a maximum when the two decay rates are coincident. Improved signal-to-noise is obtained because the noise at each instant is proportional only to the magnitude of the signal amplitude at that time.
The gain setting of the correlator depends on the trap concentration, and a good first guess is five. The correlator itself takes care of the synchronous bias pulse requirement for DLTS by retriggering the pulse each time the weighting function signal crosses a run-down discriminator. The multiplier output of the correlator should be monitored on the oscilloscope, as should the output from the Boonton 72B to the correlator input. Observing these waveforms gives an indication of when trap emission transients are occurring, and the correlator gain can be adjusted accordingly. A DC output of 5 V or more from the correlator will cause the overload light to come on—this is a warning that the input stage of the correlator will soon saturate, and the resultant DLTS peak will be flat topped.

The set of time constants available is 0.01 - 100 ms, although spectra are usually not taken below 3 ms due to interference from the long recovery time constant of the Boonton 72B, and the fact that the correction to the time constant arising from the difference between hold-time and bias pulse width (typically 200 - 400 μs) becomes significant compared to the weighting function time constant itself.

The holding time control allows a delay (1 μs - 10 ms) in retriggering of the bias pulse, and provides time for the capacitance meter to recover from the overload produced during the trap loading process, before the cross-correlation begins. A calibration function similar to the weighting function may be used to provide an input to the correlator for an absolute calibration of the system response.

5. **COLLECTION OF DATA**

For recording the capacitance transient spectrum of a sample, an appropriate reverse bias should be applied (typically 5 - 10 volts, being mindful of the leakage current) with an equivalent bias reduction pulse of typically
200 - 300 μs duration. The bridge should be set one range below that on which you would normally read the capacitance, and if possible on the 10 or 30 pF ranges. They are the least noisy ranges. This is a further reason for using small samples. The sensitivity of the Boonton 72B is the same for each pair of ranges, i.e. the 1 and 3 ranges have the same sensitivity. The balancing capacitors should be adjusted to give an above null reading—final trimming is done near -200 K for Ge, or RT for Si and GaAs. These are the temperatures below which defects will be observed, i.e. they are roughly equivalent to half the respective band gaps.

A correlator time constant of 3 or 10 ms should be selected, with a holding time of several hundred μs longer than the bias pulse width. The attenuation resistor network between the bridge output and correlator input is usually set at 1:3.6, and the y-axis of the x-y plotter at 500 mV per inch.

The x-axis is calibrated by switching the temperature control-box to the 0, 100, 200, and 300 °K settings and adjusting the Zero and Range knobs of the x-axis input accordingly. When the control-box is switched to the T setting the x-axis is driven by the output of the Lakeshore Cryotronics DRC 80 cryogenic thermometer.

5.1 Trap Activation Energy. To obtain the defect activation energy, spectra should be recorded for five or six time constants between 3 and 100 ms (see Table 4). As the correlator time constant is increased, the peak position shifts to the left (i.e. the temperature at which it appears is lower—carrier emission is slower at lower temperatures). The spectra should be recorded over an up and down temperature scan for each correlator time constant to check for hysteresis effects (see computation in Chapter 6).
5.2 Trap Cross Section. To measure deep level cross sections, stabilize at the peak temperature for a correlator time constant of 10 ms (this is arbitrary but makes reading of the signals from the oscilloscope easier), and measure and record the correlator DC output as a function of bias pulse length, as shown in Table 5—remember that the pulse duration must not be on the saturation filling region but on the region where there is an increase of signal with pulse width. Disconnect the y input of the x-y recorder and connect it to an oscilloscope for measurement.

5.3 Trap Concentration. Similarly for the trap concentration, record the correlator DC output as a function of bias pulse amplitude, as shown in Table 6, for a saturating pulse length. Generally one tries for 10 V reverse bias and the same bias pulse amplitude, as this is the maximum output amplitude from the pulser and allows the maximum depletion depth investigation. The transient capacitance change for a saturation bias pulse (in amplitude and duration) is noted from the CRT screen (Fig. 11). The oscilloscope may be calibrated directly in pF by observing the voltage shift of the DC bias capacitance signal from the Boonton 72B (connected to input to correlator) as the trimmer capacitors on the balancing arm of the bridge are increased a known amount, e.g. changing the balancing capacitance by 1.4 pF is equivalent to a 20 mV change in the output of the Boonton 72B on the 30 pF range, with the attenuation network set at 1:3.6. Thus one knows that under these conditions, a capacitance transient pulse height $\Delta C$ of 1 cm on the 20 mV per cm range of the oscilloscope is equivalent to 1.4 pF. Knowing $\Delta C$ in pF, and the bulk capacitance of the diode at that reverse bias (read directly from the Boonton 72B scale) then the concentration of each defect level is easily obtained.
5.4 Capacitance Temperature Measurements. C-V characteristics are recorded at 77 K and at any peak temperature in between—the calculation of the net background doping density is obtained from these. On the final upward scan a C-T run is useful—the appropriately labeled lead from the rear of the bridge is connected to the y-input of the plotter and the y-axis polarity of the x-y plotter is changed over—this is actually the correct polarity, as the normal correlator output signal is inverted (we run DLTS spectra in the opposite polarity to give positive going majority carrier trap peaks). The C-T dependence is a useful check on the presence of traps and can give concentration information from the size of each step in the scan. One may then calculate the \( \Delta n \) required to get this increase in capacitance. This is identically the trap concentration. An equivalent method measures the C-V of the sample at a temperature just on either side of the capacitance step—the increase at the higher temperature will be due to the trap ionization. An example of a C-T is shown in Fig. 12.

6. **Calculation of Defect Parameters**

6.1 Energy Level. The basic equation is the detailed balance relation:

\[
\frac{1}{\tau_c} = e_n = \frac{\sigma_n \langle v_n \rangle}{g} \frac{N_c}{e^{\frac{\Delta E}{kT}}} - \frac{(\Delta E)}{kT}
\]

where 
- \( e_n \) = emission rate of trap for electrons;
- \( \sigma_n \) = capture cross-section of trap for electrons;
- \( \langle v_n \rangle \) = average thermal velocity of electron at temperature \( T \);
- \( g \) = degeneracy of trap;
- \( N_c \) = density of states in conduction band at \( T \);
- \( \Delta E \) = energy separation of trap level from conduction band; and
- \( k \) = Boltzmann's constant.
Thus \(\ln \tau_c = \ln \frac{q}{\sigma_v \langle \nu_n \rangle N_c} + \frac{\Delta E}{kT} = \text{constant} + \frac{\Delta E}{kT}\)

Hence a plot of \(\ln \tau_c\) VS \(1000/T\) will have slope \(\Delta E/k\) and intercept proportional to the capture cross section. The data collected (e.g. Table 4) should be plotted as in Fig. 13. This is a personal preference—others plot \(e_n\) or \(en/T^2\) vs \(1000/T\). The slope is calculated as shown in Table 4, and the raw energy obtained from:

\[\Delta E(\text{eV}) = \text{slope} \times k \quad k = 8.614 \times 10^{-5} \text{ eV K}^{-1}\]

This is corrected for the \(T^2\) dependence of \(\langle \nu_n \rangle N_c\) by subtracting \(2kT\) where \(T\) is the average temperature over which the data was collected.

The intercept of the graph obtained also by least squares analysis can give the trapping cross-section of the defect for that carrier (e.g. hole for hole trap). The degeneracy factor is unknown for most deep levels and can be assumed to be \(g = 2\). \(N_c\) and \(\langle \nu_n \rangle\) may be obtained by substituting the appropriate average absolute temperature of measurement into the equations in Table 7. This is the cross section of the trap measured in the neutral material—it is usually different (often by an order of magnitude) from the directly measured cross section, using the signal vs bias pulse length method.

The energy levels measured depend on the temperature at which the peaks appear and the cross section of the defect. In Ge the energies may range from 30 meV at ~ 20 K to mid gap and greater at 180 K. Cross sections derived from the intercept fall usually into the range \(10^{-14} - 10^{-18} \text{ cm}^2\). Error limits on energies are typically \(\pm 10\%\), and on cross sections \(\pm 30\%\).

6.2 Cross Sections. The basic equation conveys that the number of traps filled depends exponentially on the filling pulse width:
\[ n(t) = N_T \left( 1 - \exp\left(\frac{-t}{\tau}\right) \right) \]

where \( n(t) \) = number of traps filled for pulse width \( t \);
\( N_T \) = saturated trap concentration; and
\( \tau^{-1} \) = rate of carrier capture by traps.

The relative increase in DLTS signal is related to the pulse width by:

\[ \frac{N_T - n(t)}{N_T} = \exp\left(\frac{-t}{\tau}\right) \]

\[ \ln \frac{N_T - n(t)}{N_T} = -\frac{t}{\tau} \]

This capture rate is determined from the slope of the graph shown in Fig. 14, i.e. a graph of \( \ln \frac{N_T - n(t)}{N_T} \) versus \( t \) has slope

\[ \tau^{-1} = \sigma < \n > \text{n} \]

\[ \sigma = \frac{\text{slope}}{< \n > n} \]

where \( n \) = doping density derived from the slope of the C-V characteristic. In other words, \( N_T \) is the saturated signal output, and \( n(t) \) is the signal output for pulse width \( t \). Table 5 contains a sample calculation.

These equations are relevant for majority carrier traps only. Usually one does not know the injection efficiency of a forward biasing (or LED) pulse and hence the injected carrier density is subject to large calculational errors. Others have proposed methods for estimating the various parameters, but my personal view is that one can derive a number for the cross section of a minority trap from its Arrhenius (energy level) plot, and that this is as good a number as any other that might be calculated.

6.3 Concentration Profiles. The relative change in DLTS output signal for a small change in the bias pulse amplitude \( V \) is given by:
\[
\delta \left( \frac{\Delta C}{C} \right) = \frac{\varepsilon}{2qW^2} \times \frac{N_T(X)}{N(X)} \times \delta V
\]

where \( X \) is the depletion layer width during the bias pulse and \( N_T \) is the trap concentration.

\[ W = \sqrt{\frac{2\varepsilon V}{qN}} \] is depletion layer width for the applied bias;

\( C \) = capacitance at the applied reverse bias; and

\( N \) = net impurity density at the edge of the depletion layer.

In general \( N = N(X) \) so:

\[ \delta \left( \frac{\Delta C}{C} \right) = \text{constant} \cdot N_T(X) \cdot \delta V \]

or \( N_T(X) = \text{constant} \cdot \frac{\delta (\Delta C)}{\delta V} \)

If one plots the relative output signal versus \( V_p \) (Fig. 15a) and obtains a straight line then the trap concentration profile follows the profile of the net free carrier density which is generally constant (see also Table 6).

The most used equation for trap concentration is:

\[ N_T = 2\frac{\Delta C}{C} (N_D - N_A) \text{ for } \frac{\Delta C}{C} < 0.1 \]

where \( N_D - N_A \) comes from a C-V measurement, \( \Delta C \) = capacitance change for a saturating pulse is read on the oscilloscope screen, and \( C \) is the quiescent reverse bias capacitance.

An example of a concentration determination in a Ge diode is given below (see Fig. 15b):

\[ \Delta C(V_2) = 4 \text{ pF for } V_R = 8V, V_2 = 8V \]

\[ \Delta C(V_1) = 3 \text{ pF for } V_1 = 6V \]

\[ \delta V_1 = 2V \]

\[ C = 119 \text{ pF} \]

\[ A = 1 \text{ cm}^2 \]

\[ N = 10^{12} \text{ cm}^{-3} \]
Then \( \bar{N}_T(X) = \frac{q\varepsilon_0 A^2 N^2}{C^3} \times \frac{\Delta C(V_2) - \Delta C(V_1)}{\delta V_1} \)

where \( V_1 = \text{initial pulse height} \)

\[ \begin{align*}
V_2 &= V_1 + \delta V_1 \\
X &= \left( \frac{2\varepsilon_0 (V_R - V_1)}{qN} \right)^{\frac{1}{2}}
\end{align*} \]

Thus \( \bar{N}_T(X) = \frac{1.6 \times 10^{-19} \times 16 \times 8.84 \times 10^{-14} (1)^2 (10^{12})^2}{(119 \times 10^{-12})^3} \left[ \frac{(4 - 3) \times 10^{-12}}{2} \right] \text{cm}^{-3} \)

\[ = 6.7 \times 10^{10} \text{ cm}^{-3} \]

or \( \bar{N}_T = 2 \frac{\Delta C}{C} N = 2 \times \frac{4}{119} 10^{12} = 6.7 \times 10^{10} \text{ cm}^{-3} \)

These answers are the same since the concentration profile is linear. In the latter case \( N_T \) is the average over the whole depletion region \((12 \mu \text{m})\).

In the former case \( N_T \) is the average over the first 2 \( V \) region of the depletion depth, i.e. 6 \( \mu \text{m} \). A nonlinear profile determined by this method is shown in Fig. 16. Errors are typically \( \pm 25\% \).

6.4 Net Doping Density. The effective background doping of an abrupt junction sample is derived from the slope of a \( 1/C^2 \) vs \( V \) plot (Fig. 17).

Again this is a personal preference. Others plot \( \log C \) vs \( \log V \) and compare the slope to the expected value of \(-1/2\). For the \( C^{-2} \) vs \( V \) method, the basic equation is:

\[ C = \frac{q\varepsilon_s N_B}{\sqrt{2(V_{bi} + V)}} \] pF/cm²

\[ \Rightarrow \frac{1}{C^2} = \frac{2}{q\varepsilon_s N_B} (V_{bi} + V) \]
\[ \frac{d\left(\frac{1}{C^2}\right)}{dV} = \frac{2}{q\varepsilon_s N_B} \text{ for unit area} \]

- the slope of \( C^{-2} \) vs \( V \) equals \( \frac{2}{q\varepsilon_s N_B} \)

\[
i.e. \quad N_B = \frac{2}{q\varepsilon_s \text{slope} A^2} = \frac{8.84 \times 10^{30}}{\text{slope (in F}^{-2}\text{) x A}^2(\text{in cm}^4)} \quad \text{for Ge}
\]

The net free carrier concentration profile can be obtained from:

\[ n(x) = \frac{-C^3}{\varepsilon q A^2} \left(\frac{dC}{dV}\right)^{-1} \]

where \( \frac{dC}{dV} \) is the slope of the C-V plot.

6.5 Current-Temperature Dependence. These plots can be recorded point by point by connecting the LO lead of the sample to an electrometer. The HI lead is still connected to the Boonton 72B, and it is through this lead that the bias is applied. Because the Boonton and the electrometer have a common ground through the shields of their input connectors, there is no need to connect the two together. The bias is read off the usual multimeter and the sample temperature can be accurately read off by comparing the Si thermometer diode voltage to the calibration chart. The measurements are better done in vacuum (closed cycle refrigerator cryostat) and during an upward temperature scan (to reduce interference from the compressor vibration). An example from a Si(Li) radiation detector coated with a-Si(H) is shown in Fig. 18.

6.6 Forward Bias Pulsing; LED Injection. For p-n junction samples, use of a forward bias pulse (typically ~ 1.5 V greater than the standing reverse bias) provides an injection of minority carriers which will reveal minority
carrier traps, if present. On Schottky barrier samples, pulsed illumination from a band-edge light will achieve a similar result. Both techniques, however, suffer from drawbacks. With a LED one cannot be sure whether the defects are bulk or surface states, while forward bias pulsing may produce severe overloading of the 1 MHz oscillator in the Boonton 72B. This may be circumvented to some extent by using the available MOSFET gate connector. The LO lead of the sample is connected to one side of this attachment, the bias pulse is applied to the center connector, and the other side of the attachment goes to the LO side of the Boonton 72B. The aim of the device is to gate out the Boonton during the injection pulse, avoiding the overloading problem. To use the available light source, disconnect the bias pulser output to the Boonton and short this lead out (an appropriate connector is available). Change the pulser polarity to negative, and connect the LED input lead to the pulser output. Use a pulse of 4 – 5 V, 100 µs duration. The ACOPIAN power supply provides voltage for the laser source, and is turned on, and its output adjusted so that the laser is just drawing a current. The light source is useful for Ge only—other LED's should be used for wider band gap materials.

One may also use two bias pulses for trap filling. It is possible to measure the minority carrier cross section of a majority trap (e.g. the hole capture cross section of an electron trap) by injecting minority carriers with the first pulse, then using a second saturating pulse to fill the traps with majority carriers, i.e. emit their minority carriers. By plotting signal destruction vs. pulse width of the second pulse, one may obtain the minority carrier capture cross section, though one must still know the injected minority carrier concentration. The technique is useful for checking defects in the zero bias depletion region. One can single out the region by using an injection pulse into the region, and the second saturation pulse to "fold back" the depletion
region to the zero bias depth, i.e. one is looking at the difference between the regions investigated by the two pulses.

7. MILLER PROFILER

The Lehighton Miller profiler allows the net shallow impurity profile within a diode sample to be automatically plotted. Its applicability to research samples is somewhat limited by the constraints it sets on sample size ($< 5 \times 10^{-2}$ cm$^2$), capacitance ($< 500$ pF at all voltages), leakage current ($< 10^{-6}$ A at all voltages) and impurity content ($10^{14} - 10^{19}$ cm$^{-3}$). It is designed for commercially available diodes, but has found some application with low resistivity Si samples (Fig. 19). The profiler manual sets out in detail how to generate such plots.

8. HIGH TRAP CONCENTRATIONS

Apart from using the constant capacitance DLTS mode to overcome the problem of non-exponential conditions in samples with high trap concentrations, one may also apply corrections to the data obtained from such samples. The corrections entail measurement of $\Delta C$ as a function of temperature, and comparison of this with the theoretical response expected. Account may then be taken of the effect of the non-exponentiality on the measured time constant, and thus corrected Arrhenius plots can be obtained [16].

9. POOLE-FRENKEL EFFECT, RECOMBINATION-ENHANCED ANNEALING

The electric field within a junction diode sample can affect the emission of trapped carriers in the depletion region. To check for this effect, at constant reverse bias the filling bias pulse amplitude is reduced, sampling lower field regions within the depletion region. At high enough fields
the Coulombic barrier to emission of a trapped carrier is reduced, and the defect state shows a higher emission rate at constant temperature. This is observed on a DLTS spectrum by noting a shift in peak position as the field strength is altered. This Poole-Frenkel effect leads to an emission rate that is both field and temperature dependent. The usual detailed balance relation:

\[ n_p (T) = A T^2 \exp \left( \frac{\Delta E_T}{kT} \right) \]

becomes \( n_p (E,T) = n_p (T) \exp \left( \frac{\Delta E}{kT} \right) \)

where \( \Delta E = \left( \frac{qE}{\pi\varepsilon} \right)^{1/2} \) is the barrier lowering in eV by an applied field \( E \).

Since \( \Delta E \) depends on the charge of the ion that has detrapped a carrier, this method may be used to identify the charge state of defects giving rise to DLTS peaks. (At high enough fields, \( > 10^5 \text{ V cm}^{-1} \), tunneling of trapped carriers may also become important.) Determination of the charge state of a defect enables one to assign a donor or acceptor tag to the center. If a defect has trapped a majority carrier, and displays the P-F effect, then it is the same type of defect as the majority shallow level dopant (e.g. donor in n-type material). If it does not display the P-F effect, then it is the opposite type (e.g. acceptor in n-type material). One must remember that deep states have significant capture rates for both electrons and holes. The slope of a plot of \( E_T - \Delta E \) versus \( (E_{\text{average}})^{1/2} \) yields the Poole-Frenkel constant \( (q/\pi\varepsilon)^{1/2} \) for that particular semiconductor [17].

Recombination enhancement is any reaction path in which vibrational energy deposited locally at a defect by a non-radiative electronic transition serves to increase the reaction rate. Recombination enhanced defect annealing occurs when electron-hole pairs recombine at the site of a defect, creating a high local energy density which may be enough to dissociate the defect [18]. Such
energy deposition can cause enhancement of other defect reactions e.g. diffusion. The susceptibility of defects to recombination enhanced annealing can be tested by leaving diode samples heavily forward biased (A/cm² injection current density) at room temperature for several hours, and rechecking the DLTS spectrum to look for defect removal.

10. MISCELLANEOUS

10.1 Alloy Broadening of Levels. The normal width of a DLTS peak, assumed to be Gaussian, is approximately 0.14 T_M, where T_M is the peak temperature. Non-resolved multi-level peaks are quite common in DLTS, as evidenced by peaks broader than expected. However, activation energies derived from the normal analysis are quite valid [19]. In the case of alloy broadened levels, e.g. EL2 in AlGaAs or GaAsP, there exist methods of obtaining the deep level energy distribution and corrected concentration from straightforward measurements of peak width and a knowledge of the alloy composition [19].

10.2 DLTS Uniaxial Stress Experiments. As mentioned in the introduction, DLTS gives a wealth of information on the electronic properties of deep levels in semiconductors, but does not give clues as to the microscopic nature of the centers. This can be overcome to some extent by the application of uniaxial stress to the diode during a standard DLTS scan. At high enough stress this can result in the splitting of a peak due to stress induced electronic reorientation of the centers which depends on the symmetry of the defect [20]. Combination of this technique with the polarized excitation photocapacitance technique of Stavola and Kimerling [21] may clarify the nature of a number of important defects in semiconductors.
10.3 Near Surface Concentration Profiles. For near surface profiling of defects, one must take into account the effects of the edge region of the depletion depth, because during the bias pulse the region where deep levels are filled with carriers is larger than that where the shallow levels are neutralized by the injected carriers, i.e. one must calculate the distance into the edge region of the depletion layer over which traps are filled by the majority carrier pulse. The standard profiling equation then becomes:

\[ N_T [W_p - \lambda (\tau_p)] = \frac{qW_B}{\varepsilon} \frac{2N_{CV}(W_B)}{N_{CV}(W_p)} \frac{\delta A}{C} / \delta V_p \]

where \( W = \varepsilon A/C \) is the depletion depth at either the standing reverse bias (\( W_B \)) or during the bias pulse (\( W_p \)), \( \lambda (\tau_p) \) is this distance into the edge region just discussed (measured from \( W_p \)), and \( V_p \) and \( \tau_p \) are the amplitude and duration of the pulse respectively. It is somewhat complex to calculate \( \lambda (\tau_p) \), and several samples are required to get all the information. Grimmeiss [22] describes one of the methods of correcting profiles for the edge effect.

11. ACKNOWLEDGMENTS

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U. S. Department of Energy to the exclusion of others that may be suitable.

This work was supported by the Director's Office of Energy Research, Office of Health and Environmental Research, U. S. Department of Energy under Contract Number DE-AC03-76SF00098.
12. REFERENCES

## TABLE 1. CONTACTS TO SEMICONDUCTOR MATERIALS

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>Ohmic</th>
<th>Rectifying</th>
<th>Comment</th>
<th>Comment</th>
</tr>
</thead>
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<td>evap. Al</td>
<td>vac. &lt; 3 x 10⁻⁷ Torr</td>
<td>evap. Au</td>
<td>vac. &lt; 10⁻⁶ Torr</td>
</tr>
<tr>
<td></td>
<td>impl. P</td>
<td>anneal 600°C, 1 h</td>
<td>impl. B</td>
<td>anneal 500°C, 1 h</td>
</tr>
<tr>
<td></td>
<td>diffuse P</td>
<td>heat &gt; 900°C</td>
<td>diffuse B</td>
<td>heat &gt; 750°C</td>
</tr>
<tr>
<td></td>
<td>diffuse Li</td>
<td>300°C, 10 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p - Si</td>
<td>evap. Au</td>
<td>vac. &lt; 10⁻⁶ Torr</td>
<td>evap. Al</td>
<td>vac. &lt; 3 x 10⁻⁷ Torr</td>
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<tr>
<td></td>
<td>impl. B</td>
<td>anneal 500°C, 1 h</td>
<td>impl. P</td>
<td>anneal 600°C, 1 h</td>
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<tr>
<td></td>
<td>diffuse B</td>
<td>heat &gt; 750°C</td>
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<td>heat &gt; 900°C</td>
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<td>evap. Au</td>
<td>vac. &lt; 10⁻⁶ Torr</td>
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<td>heat 750°C</td>
<td>diffus Zn</td>
<td>heat 750°C</td>
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<tr>
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<td>vac. &lt; 3 x 10⁻⁷ Torr</td>
<td>Au-Ge alloy</td>
<td>475°C, 2 min</td>
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<tr>
<td></td>
<td>evap. Au</td>
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<td></td>
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<td>alloy In, Al</td>
<td>475°C, 0.5 h</td>
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<td>implant B</td>
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<td>p - Ge</td>
<td>evap. Pd, Au</td>
<td>vac. &lt; 10⁻⁶ Torr</td>
<td>diffuse Li</td>
<td>300°C, 10 min</td>
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<tr>
<td></td>
<td>alloy In, Al</td>
<td>475°C, 0.5 h</td>
<td>diffuse Sb</td>
<td>650°C, 0.5 h</td>
</tr>
<tr>
<td></td>
<td>implant B</td>
<td>10¹⁴ cm⁻², 25 keV</td>
<td>implant P</td>
<td>10¹⁴ cm⁻², 25 keV</td>
</tr>
<tr>
<td></td>
<td>Ga-In rub on squeak-on</td>
<td></td>
<td>anneal 330°C, 0.5 h</td>
<td></td>
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TABLE 2. POLISH ETCHANTS FOR SEMICONDUCTOR MATERIALS

<table>
<thead>
<tr>
<th>Material</th>
<th>Etchant Description</th>
</tr>
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<tbody>
<tr>
<td>Ge</td>
<td>$3\text{HNO}_3:1\text{HF}$</td>
</tr>
<tr>
<td>Si</td>
<td>$3\text{HNO}_3:1\text{HF}$, $8\text{HNO}_3:1\text{HF}:1\text{CH}_3\text{COOH}$</td>
</tr>
<tr>
<td>GaAs</td>
<td>$3\text{HNO}_3:1\text{HF}:2\text{H}_2\text{O}$, $3\text{H}_2\text{SO}_4:1\text{H}_2\text{O}_2:1\text{H}_2\text{O}$ (60°C)</td>
</tr>
<tr>
<td>GaP</td>
<td>$3\text{HNO}_3:1\text{HF}$</td>
</tr>
</tbody>
</table>

NB These are typically used to remove saw or lap damage prior to evaporation of contacts, or annealing of the material.
### TABLE 3. STANDARD SAMPLES FOR CAPACITANCE SPECTROSCOPY

<table>
<thead>
<tr>
<th>Material</th>
<th>Procedure</th>
<th>Defects Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-type Ge</td>
<td>Plate with Cu for 10 min at 8 mA in CuCN soln.</td>
<td>Cu((44 \text{ meV}))</td>
</tr>
<tr>
<td>(N_A - N_D \approx 10^{11} \text{cm}^{-3})</td>
<td>Diffuse at 450°C for 12 h Fabricate contacts after cleaning</td>
<td>Cu(^2) (330 meV) Cu-H (various, if applicable)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>p-type Ge</td>
<td>Fabricate contacts</td>
<td>O-V levels</td>
</tr>
<tr>
<td>(N_A - N_D \approx 10^{11} \text{cm}^{-3})</td>
<td>Irradiate: 30 MRad of Co-60 (\gamma)-rays</td>
<td>(E_v + 0.23 \text{ eV}, E_v + 0.38 \text{ eV})</td>
</tr>
<tr>
<td>n-type Si</td>
<td>Fabricate contacts</td>
<td>(E_C - 0.17 \text{ eV})</td>
</tr>
<tr>
<td>(5 - 10 \times 10^{15} \text{cm}^{-3})</td>
<td>Irradiate: 100 MRad of Co-60 (\gamma)-rays</td>
<td>(V-V , E_C - 0.22 \text{ eV}) (P-V , E_C - 0.44 \text{ eV}) (V-V , E_C - 0.39 \text{ eV}) latter two often unresolved</td>
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<tr>
<td>n- or p-type Si</td>
<td>Evaporate 80 Å of Au</td>
<td>Au acceptor ((E_C - 0.54 \text{ eV})) in n-type</td>
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<td>(~10^{15} \text{cm}^{-3})</td>
<td>Diffuse at 1000°C for 20 h Evaporate contacts after cleaning</td>
<td>Au donor ((E_v + 0.35 \text{ eV})) in p-type</td>
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TABLE 4. ENERGY LEVEL DETERMINATION

<table>
<thead>
<tr>
<th>Sample: Ge(γ) 2E</th>
<th>Peak Designation: Majority 1</th>
<th>DLTS Energy</th>
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<tr>
<td>Date: 2/20/80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bias: 20v</td>
<td>Pulsing: 20v</td>
<td>Duration: 200μs τ_{CR}: 5 sec th: 0.5 Gain: 0.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>τ_c(ms) (Dial)</th>
<th>τ_{CORR}(ms) Actual</th>
<th>T(K)</th>
<th>T_{av}(K)</th>
<th>1/τ_{av} x 10^{-3}</th>
<th>τT^2 x 10^5</th>
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<td>145.18</td>
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<td>148.50</td>
<td>150.09</td>
<td>6.66</td>
<td></td>
</tr>
</tbody>
</table>

\[ \text{slope} = \frac{n \Sigma \frac{1}{T} \ln T C - \Sigma \frac{1}{T} \ln T C}{n \Sigma \left(\frac{1}{T}\right)^2 - \left(\Sigma \frac{1}{T}\right)^2} = \frac{8(184.5338002 \times 10^{-3}) - 54.06 \times 10^{-3}(27.0427168)}{[8(365.7612) - 2922.4836] \times 10^{-6}} = 3987.002 \]

\[ \Delta E = 3987.002 \times 8.614 \times 10^{-5} = 0.3434 \text{ eV} \]

\[ -2kT_{av} = 2 \times 8.614 \times 10^{-5} \times 146 = 0.0249 \text{ eV} \]

\[ \text{intercept} = - \left[ \frac{\Sigma \left(\frac{1}{T}\right)^2 \ln T C - \Sigma \frac{1}{T} \ln T C}{n \Sigma \left(\frac{1}{T}\right)^2 - \left(\Sigma \frac{1}{T}\right)^2} \right] = - \left[ \frac{9.8911765 - 9.9761405 \times 10^{-3}}{3.606 \times 10^{-6}} \right] = 23.56 \]

\[ \sigma = \frac{e^{23.56} \times g}{<v_{av}> \times N_c} \times <v_{av}> = \left( \frac{3kT}{m^*} \right)^{1/2} = \left( \frac{3k146}{1.6 \times 9.11 \times 10^{-31}} \right)^{1/2} = 6.44 \times 10^6 \text{cm.s}^{-1} \]

\[ N_c = 4.83 \times 10^{15} \times (1.6)^{3/2} \times (146)^{3/2} = 1.72 \times 10^{19} \text{cm}^{-3} \]

\[ g = 2 \]

\[ \sigma = 3.1 \times 10^{-16} \text{cm}^2 \]
TABLE 5. CROSS SECTION DATA AND DETERMINATION

<table>
<thead>
<tr>
<th>Pulse Width (µs)at</th>
<th>Correlator Output Signal Amplitude (v)</th>
<th>NT - n(t)(\frac{N_T - n(t)}{N_T})</th>
<th>ln NT - n(t) ln NT - n(t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>6.32</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>180</td>
<td>6.32</td>
<td>0.027</td>
<td>-3.61</td>
</tr>
<tr>
<td>160</td>
<td>6.31</td>
<td>0.151</td>
<td>-1.89</td>
</tr>
<tr>
<td>140</td>
<td>6.31</td>
<td>0.224</td>
<td>-1.50</td>
</tr>
<tr>
<td>120</td>
<td>6.31</td>
<td>0.332</td>
<td>-1.10</td>
</tr>
<tr>
<td>100</td>
<td>6.31</td>
<td>0.472</td>
<td>-0.75</td>
</tr>
<tr>
<td>80</td>
<td>6.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>NT = 6.29</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>60</td>
<td>n(t) = 6.12</td>
<td>0.027</td>
<td>-3.61</td>
</tr>
<tr>
<td>50</td>
<td>&quot; = 5.34</td>
<td>0.151</td>
<td>-1.89</td>
</tr>
<tr>
<td>40</td>
<td>&quot; = 4.88</td>
<td>0.224</td>
<td>-1.50</td>
</tr>
<tr>
<td>30</td>
<td>&quot; = 4.20</td>
<td>0.332</td>
<td>-1.10</td>
</tr>
<tr>
<td>20</td>
<td>&quot; = 3.32</td>
<td>0.472</td>
<td>-0.75</td>
</tr>
</tbody>
</table>

\[
slope = \frac{n\sum\Delta t \times \ln \frac{N_T - n(t)}{N_T} - \sum n \ln \frac{N_T - n(t)}{N_T} \sum \Delta t}{n\sum(\Delta t)^2 - (\sum \Delta t)^2}
\]

\[
= \frac{5(419.1 \times 10^{-6}) - 8.85(200 \times 10^{-6})}{[5(9000) - 40000] \times 10^{-12}} = \frac{[2.0955 - 1.77] \times 10^{-3}}{5 \times 10^{-8}}
\]

\[
= 6510
\]

Cross Section:

\[
\sigma = \frac{slope}{n\langle v \rangle} = \frac{6510}{6.44 \times 10^5 \times 1.1 \times 10^{17}} = 9.2 \times 10^{-16} \text{ cm}^2
\]
TABLE 6. CONCENTRATION DATA AND DETERMINATION

Sample: As Doped  
Date: 9/17/79  
Bias: 28 V

<table>
<thead>
<tr>
<th>$V_p$ (volts)</th>
<th>$\frac{V_p}{V_{pMax}}$</th>
<th>$\Delta C$ (cm)</th>
<th>$\frac{\Delta C}{C}$</th>
<th>Signal Amplitude</th>
<th>Signal Max. Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>1</td>
<td>0.7 cm</td>
<td>$1.58 \times 10^{-2}$</td>
<td>3.71</td>
<td>1</td>
</tr>
<tr>
<td>25</td>
<td>0.89</td>
<td>50 cm V/cm</td>
<td>$1.44 \times 10^{-2}$</td>
<td>3.38</td>
<td>0.91</td>
</tr>
<tr>
<td>20</td>
<td>0.71</td>
<td>30pF Boonton</td>
<td>$1.14 \times 10^{-2}$</td>
<td>2.67</td>
<td>0.72</td>
</tr>
<tr>
<td>18</td>
<td>0.64</td>
<td>= 0.77 pF</td>
<td>$9.8 \times 10^{-3}$</td>
<td>2.30</td>
<td>0.62</td>
</tr>
<tr>
<td>15</td>
<td>0.54</td>
<td></td>
<td>$8.7 \times 10^{-3}$</td>
<td>2.04</td>
<td>0.55</td>
</tr>
<tr>
<td>12</td>
<td>0.43</td>
<td></td>
<td>$6.9 \times 10^{-3}$</td>
<td>1.63</td>
<td>0.44</td>
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<tr>
<td>10</td>
<td>0.36</td>
<td></td>
<td>$5.9 \times 10^{-3}$</td>
<td>1.37</td>
<td>0.37</td>
</tr>
<tr>
<td>8</td>
<td>0.29</td>
<td></td>
<td>$4.6 \times 10^{-3}$</td>
<td>1.08</td>
<td>0.29</td>
</tr>
<tr>
<td>5</td>
<td>0.18</td>
<td></td>
<td>$3.2 \times 10^{-3}$</td>
<td>0.74</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Trap concentration linear, and $N_T = 2\frac{\Delta C}{C} (N_D - N_A)$

$= 2(1.58 \times 10^{-2}) (N_D - N_A)$

$= 3.2\% (N_D - N_A)$
TABLE 7. USEFUL NUMBERS WHEN WORKING OUT PARAMETERS

<table>
<thead>
<tr>
<th></th>
<th>Ge</th>
<th>Si</th>
<th>GaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average thermal velocity</td>
<td>$v_e = 9.1 \times 10^5 \sqrt{T}$</td>
<td>$6.4 \times 10^5 \sqrt{T}$</td>
<td>$2.6 \times 10^6 \sqrt{T}$</td>
</tr>
<tr>
<td></td>
<td>$v_h = 1.1 \times 10^6 \sqrt{T}$</td>
<td>$8.8 \times 10^5 \sqrt{T}$</td>
<td>$9.1 \times 10^5 \sqrt{T}$</td>
</tr>
<tr>
<td>(cm/sec)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density of states in relevant band (cm$^{-3}$)</td>
<td>$N_C = 2 \times 10^{15}T^{3/2}$</td>
<td>$5.4 \times 10^{15}T^{3/2}$</td>
<td>$9.0 \times 10^{13}$</td>
</tr>
<tr>
<td></td>
<td>$N_V = 1.2 \times 10^{15}T^{3/2}$</td>
<td>$2 \times 10^{15}T^{3/2}$</td>
<td>$1.3 \times 10^{15}T^{3/2}$</td>
</tr>
<tr>
<td>Depletion depth (cm)</td>
<td>$W = 4204.8 \sqrt{\frac{V + V_{bi}}{N}}$</td>
<td>$3610.9 \sqrt{\frac{V + V_{bi}}{N}}$</td>
<td>$3470.5 \sqrt{\frac{V + V_{bi}}{N}}$</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>16</td>
<td>11.8</td>
<td>10.9</td>
</tr>
<tr>
<td>Effective mass for density of states and velocity calculations</td>
<td>$m_e = 0.55$</td>
<td>1.1</td>
<td>0.068</td>
</tr>
<tr>
<td></td>
<td>$m_h = 0.37$</td>
<td>0.59</td>
<td>0.55</td>
</tr>
</tbody>
</table>

NB. All $T$ in degrees K.
FIGURE CAPTIONS

Fig. 1. DLTS spectrum of Cu diffused p-type Ge crystal grown from quartz crucible under a H₂ atmosphere. Reverse bias \( V_R = 10 \) V, bias pulse \( V_p = 10 \) V (200 \( \mu \)s), correlator time constant \( E_C = 10 \) ms.

Fig. 2. DLTS spectrum of p-type Ge irradiated with Co-60 γ-rays (dose = 30 MRad). The two peaks are due to O-V complexes.

Fig. 3. DLTS spectrum of γ-irradiated n-type Si showing the characteristic peaks obtained; the negative going peak is obtained under forward bias conditions.

Fig. 4. DLTS spectrum from Au diffused p-type Si, showing the Au donor level.

Fig. 5. DLTS spectrum from Au diffused n-type Si, showing the Au acceptor level.

Fig. 6. Variation of p-n junction sample capacitance with reverse bias \( V_R \).

Fig. 7. Pulsing waveforms for observation of capacitance transients.

Fig. 8. Method of calculating activation energy of deep level center from emission-rate dependence of DLTS peak position.

Fig. 9. Pulsing sequences for DLOS and DLTS modes of capacitance spectroscopy (from Ref. 14).

Fig. 10. a) Schematic diagram of Janis He gas exchange dewar, and b) operating instructions (including the following two pages).

Fig. 11. Measurement of ΔC from oscilloscope screen.

Fig. 12. Typical C-T (1 MHz) for a γ-irradiated p-type Ge sample.

Fig. 13. Arrhenius plot of γ-irradiation-induced level in p-Ge.

Fig. 14. Cross section determination for level in n-type Ge.

Fig. 15a. Concentration profile for γ-induced level in p-Ge.

Fig. 15b. Explanation of symbols used in the sample calculation on page 19.

Fig. 16. Non-linear trap profile in GaAs.

Fig. 17. C-² versus \( V_R \) plot for a Ge diode showing calculation of net doping density.

Fig. 18. I-T plot obtained from a Si(Li) diode at 50 V bias. The current is measured on an electrometer, the temperature by noting the thermometer output voltage and comparing with the calibration chart.

Fig. 19. Miller profile plot of space charge concentration in a low resistivity Si diode, showing compensation of the shallow dopant boron near the surface.

Fig. 20. Block diagram of Miller correlator.
P TYPE Ge
Cu DIFFUSED
$V_R=10V$, $\tau_C=10mS$

![Graph showing samples temperature (K) against correlator output (arbitrary units). Peaks labeled Cu-H RELATED and Cu-2+ are visible.](XBL 8312-4738)
Figure 2.

GE Co #7
$V_R = 10V$, $V_P = 10V(200 \mu S)$
$\tau_C = 10mS$

$E_V + 0.23eV$

$E_V + 0.38eV$
Si:P:CZ

$10^{15}$ cm$^{-3}$

$\gamma$-IRRADIATED

$V_R=5V$, $T_C=10\text{mS}$

---

**Figure 3.**

**CORRELATOR OUTPUT (ARBITRARY UNITS)**

- $E_C - 0.17eV$
- $E_C - 0.22eV$
- $E_C - 0.44eV$
- $E_V + 0.42eV$

**SAMPLE TEMPERATURE (K)**

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Correlator Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>77</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td></td>
</tr>
</tbody>
</table>

XBL 8312-4739
Si:B:CZ

Au DIFFUSED

$P = 1 \times 10^{15} \text{ cm}^{-3}$

$V_R = 5 \text{ V}, \tau_C = 10 \text{ mS}$

Sample Temperature (K) vs. Concentration ($\times 10^{13} \text{ cm}^{-3}$)
Si:P:CZ

Au DIFFUSED

n = 8 \times 10^{14} \text{ cm}^{-3}

V_R = 5 \text{ V}, \tau_C = 10 \text{ mS}

E_C = 0.54 \text{ eV}
Capacitance \[ C = \frac{\varepsilon A}{W} \]

Depletion Depth \[ W = \left( \frac{2\varepsilon (V_{bi} + V_R)}{qN} \right)^{1/2} \]

Fig. 6. Reverse Biased Diode--Area \( A \) cm\(^2\), doping density \( N \) cm\(^{-3}\), built-in bias \( V_{bi} \).
Depleted n Type Material

Deep Level Traps

Conduction Band $E_C$

Valence Band $E_V$

Applied Bias

$-V_R$

$W(t)$

Contraction of Space Charge Region

$\tau_D = e^{E_T/kT}$

$C(t)$

Figure 7.
Figure 8.
Figure 9.

- **Electrical DLTS**
- **Thermal DLTS**
- **Optical DLTS**

### Electrical DLOS
- Voltage (V)
- Bias (V_b)

### Thermal DLOS
- Photon flux (Φ)
- Slow sweeping rate
- Dark

### Optical DLOS
- Capacitance (C)
- T = const (low temperature)
- T = const (high temperature)
- T = const (low temperature)
- Photon flux correction (Φ_correct)

**Data Processing**
- Sampling, averaging, evaluation of \( \frac{d}{dt} \Delta C(t) \) at \( t = 0 \)
- Photon flux correction

**Parameter**
- T parameter
- No parameter
- \( h\nu_{ex} \) (excitation) parameter

**Evaluation**
- 1 peak = 1 level

- Electroluminescence
- Thermal luminescence
- Optical luminescence

- Photoluminescence
- Electroluminescence
- Photoluminescence

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Figure 104.

- Optional dry test gas meter.
- To monitor actual helium usage.
- Rate of superconducting system.

- Full port isolation valve for mechanical vacuum pump.
- Safety pressure relief valve (set at ~2 psia).
- Small (1/8") full porting isolation valve for connecting to monitoring sample tube.
- Flexible hose at least 5 feet long.
- Small gauge isolation valve for additional safety.
- Compression gauge can also be attached to monitor sample tube pressure.
- Useful in determining liquid.
- Sample temperature is recommended if reduced.
- Small vacuum valve for venting or venting of sample.

- Wood framing part.
Figure 10b.
BASIC OPERATION OF "SUPER VARITEMP" SYSTEM

1) Attach a mechanical vacuum pump to the vapor pumping port (a) at the top of the cryostat. Continuously evacuate the sample tube (b).

2) Precool the cryostat with liquid nitrogen. The Helium reservoir may be precooled with liquid nitrogen or back filled with helium gas.

3) If liquid nitrogen is used to precool the helium reservoir, blow out using helium gas and leave the reservoir back filled (with helium gas).

4) Open the helium throttle valve control (c) approximately one turn and listen for the "gurgle" from the vacuum pump. This indicates the valve (d), the helium capillary (e), and the vaporizer (f) are clean and open. The entire sample tube (b) will then be purged with helium gas. Upon purging the system, the helium valve should then be closed, finger tight (do not overtighten or the valve may freeze shut due to the contraction of the disimilar materials used in the valve body and needle assembly).

5) Fill helium reservoir to desired volume of liquid helium. Upon initiation of helium transfer, repeat step (4). It is a good idea to continue to repeat step (4) several times during the filling operation to insure the entire "Super Varitemp" system remains clean and open to proper helium flow.

6) Upon completion of the liquid helium transfer, install the helium reservoir pressure regulator (g). Be sure other access ports to the reservoir are closed and sealed. The regulator will then maintain a positive pressure(2 to 4 psig, depending upon the system) which both precludes the admission of air to the helium reservoir and provides a constant drive pressure for the liquid helium across the helium throttle valve (d).

7) Once the helium reservoir is pressurized, the mechanical vacuum pump should be valved off (see the suggested manifold assembly shown in Figure 2) and the helium valve control (c) opened anywhere from two to six turns. The vaporizer assembly (f) will cool down and liquid helium should collect at the bottom of the sample tube within a few minutes (depending upon valve opening, sample tube size and mass of flanges and window mounts involved).

8) Once liquid helium collection has been accomplished, the helium valve control (c) should be reclosed to approximately 90° to 120° (of one turn) open and either a vaporizer heater power supply or an automatic temperature controller attached to the electrical feedthrough (h) on the evacuation valve. It is important to note that once the pressure in the sample tube (b) exceeds atmospheric pressure, it must be vented to either atmosphere or to a helium recovery system - otherwise the back pressure in the tube could preclude the actual collection of liquid helium. An excellent way of monitoring this pressure is to install a compound pressure gauge in the valve manifold assembly (see figure 2) at the mechanical pump.

9) The "Super Varitemp" system is now ready to operate. For normal efficiency, the vaporizer heater current should be set to approximately 50-75 ma and the helium valve control (c) adjusted so that the temperature in the sample zone (i) is approximately 8°-10°K. These values will vary depending upon the particular

Figure 10b.
system parameters involved, but can be considered a good "rule of thumb" to start from. At this point, temperature can be varied from 5° to 300°K, merely by changing the vaporizer heater power - it is not necessary to adjust the helium valve control (c) again unless maximum efficiency of helium usage is desired.

10a) To obtain temperatures from below 2°K to approximately 20°K, with the sample in vapor, the helium valve control (c) should be closed, the vent valve of the manifold assembly (Figure 2) should be closed, and the mechanical vacuum pump isolation valve fully opened. Once the sample tube (b) is evacuated, the helium valve control (c) should be slightly opened and adjusted until a pressure of approximately 3 to 5 TORR can be maintained in the sample tube (b) with a vaporizer heater current of approximately 100 to 150 mA. The temperature of the sample zone (i) can then be adjusted by vaporizer heater power alone.

10b) To obtain temperatures from below 2°K to 4°K, with sample in liquid helium, the vaporizer heater should be turned off, the helium valve control (c) should be fully opened and the sample tube (b) flooded with liquid helium. The helium valve can either then be closed and the liquid helium pumped to the lowest possible temperature (vent valve closed and pump isolation valve open), or the helium valve can be throttled in order to continuously replenish the liquid helium in the sample tube. The latter method naturally limits the lowest achievable temperature somewhat.

11) In order to change samples in the "Super Varitemp" system (temperatures of 4°K and above), it is only necessary to remove the sample holder from the top of the sample tube and then reinsert the holder with the new sample. During this time, the helium vapor flow in the sample tube should be maintained, or even increased, in order to preclude the admission of any air to the sample zone. When operating below 4°K, the temperature should be brought back to 4°K and the pressure to 760 TORR before removing the sample holder.

12) Shutting down procedures for the "Super Varitemp" system are quite straightforward. The helium valve control (c) should be closed, the vaporizer heater power turned off, and ideally, the sample tube (b) continuously evacuated until the entire system has returned to room temperature. If this presents a problem, the sample tube can just be valved off (close all valves shown in the manifold assembly of Figure 2) until the entire system reaches room temperature. All "Super Varitemp" sample tubes are protected with an overpressure relief valve to avoid dangerous pressure increases due to evaporating liquid left in the sample tube.

---WARNING---

The vaporizer heater (f) must not be energized when there is no helium flow present. The extreme thermal isolation achieved through the basic system design will allow the vaporizer to quickly reach destructive temperatures and either burn out the heater or melt the soft solder joint commonly used at the bottom of the assembly.

Figure 10b.
Figure 11.

(a) MAJORITY CARRIER TRAP

(b) MINORITY CARRIER TRAP
Figure 12.

HP P TYPE Ge
γ-IRRADIATED

$V_R = 10V, \; T_C = 10mS$

SAMPLE TEMPERATURE (K)

CAPACITANCE (pF)

DLTS

C-T (1MHz)
FIG 13. ARRHENIUS PLOT P-TYPE GERMANIUM ACCEPTOR LEVEL

Slope = 4716.3
\[ \Delta E = \text{Slope} \cdot k \]
\[ -2kT = 0.027 \text{ eV} \]
\[ \Delta E = 0.38 \text{ eV} \]
Intercept = 3.89x10^3
\[ \frac{1}{T} = \frac{\text{ln(intercept)} + g \cdot 3 \cdot 10^{-16} \text{ cm}^2}{N_v \langle v \rangle} \]

- \( g \) = Degeneracy factor
- \( N_v \) = Density of states in valence band
- \( \langle v \rangle \) = Average thermal velocity of hole

FIG 14. N-TYPE GERMANIUM DONOR LEVEL

Slope = 33583
\[ \frac{1}{N(t)} \cdot \text{Relative Correlator} \]
\[ \frac{N(t)}{N_0} \cdot \text{Output} \]

FIG 15a. P-TYPE GERMANIUM ACCEPTOR LEVEL

Reverse bias 30V
Linear plot follows free carrier profile
\[ N_v(x) = n(x) \]
Figure 15b.
Figure 16. Trap profile of deep donor level in GaAs.
Figure 17.

Ge 5A

$T = 77\, \text{K}$

$f = 1\, \text{MHz}$

Slope $= 1.57 \times 10^{10}$

$n = \frac{2}{q \xi_s \text{slope}} = 5.63 \times 10^{10} \, \text{cm}^{-3}$
Si(Li)
BARE SURFACE
50V BIAS

Figure 18.
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