

Concept of electrical measurement

Electrical and electronic

measurements of materials are among the most powerful techniques available for materials characterization. These measurement can reveal information that completely characterizes the electrical transport properties of a material.

Conductivity measurements yield information on the conductivity (or resistivity) of materials and indirectly the mobility of current carriers. Resistivity is one of most sensitive measures of the electrical transport in materials. Measurement includes both AC and DC techniques. The Hall effect is the versatile technique, yielding such information as carrier concentration and mobility and indirectly, estimates of scattering mechanism, all of which affect the conductivity as a function of temperature.

Careful experimental techniques can also yield information about the ionization energy of dopants contributing to the electrical transport. These measurements, used in conjunction with spectroscopies, can give information about the band structure of semiconductors.

Two Point Probe Technique (Principle):-

The conductivity or resistivity of a bulk sample is based on accurate measurement of both resistance and the sample dimensions. The resistance is the ratio of voltage across the sample to the current driven through the sample.

For a homogeneous bar of length L , and uniform cross-section A , the resistance R , is related to the resistivity ρ by

$$R = \frac{\rho L}{A} \quad \rightarrow (1)$$

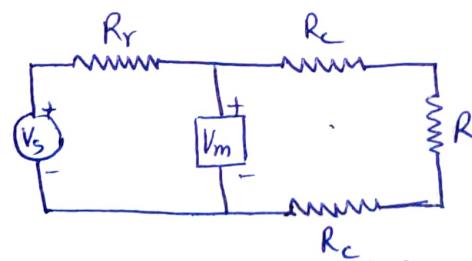
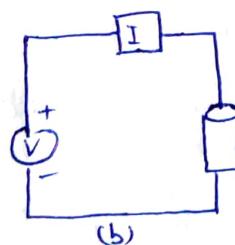
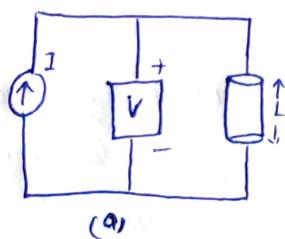


Fig. 1: Two point measurement

Fig. (2) - Two-point ohmmeter measurement circuit, which includes contact cable resistance R_c .

In fig 1. the bar is connected in a "two point" arrangement, so called, since the measurement apparatus is connected to the bar at the two end points.

The measurement apparatus is represented by an ideal current source in parallel with a high impedance voltmeter. The apparatus can also be realized using an ideal voltage source in series with a low impedance ammeter as shown in fig(a) and fig(b).

A more realistic view of a two point measurement using an ohmmeter is shown in fig(c). A voltage source and a variable orange resistor (R_r) supply the current, where R_r is adjustable to provide a convenient voltage across the voltmeter. Typical values of R_r range from 100 to 10,000 Ω . R_c represents series resistance in the cable and the wire to sample contact resistance. The resistance in the bar is calculated as

$$R = \frac{(R_r V_m / V_s)}{(1 - V_m / V_s)} - 2 R_c \quad \rightarrow (2)$$

A long bar of resistive material is desirable to minimize the effect of extra resistance in the measurement system or inaccurate length measurement.

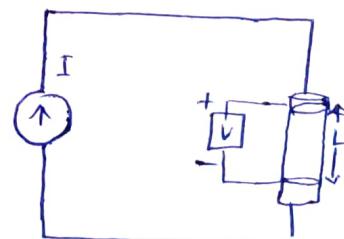
four point Probe technique:-

A more accurate method, especially for low-resistance materials, is provided by the "four point arrangement", fig(c).

The resistance now is a function of the length bw the voltage probe L' or

$$R = \frac{c L'}{A} \quad \rightarrow (3)$$

The current through the high-impedance voltmeter is very small and minimizes the effect of the cable and contact resistance. The four point approach, when used with a micro-ohmmeter, is capable of measuring down to $10^{-7} \Omega$.



fig(c) four point measurement tech.

Practical aspect of the method:-

The two point approach is most accurate for high resistance measurements where the usually small R_c term (less than 2Ω) can be ignored. These measurements are often made using ohmmeter contained within the multimeters capable of measuring Voltage, current and resistance.

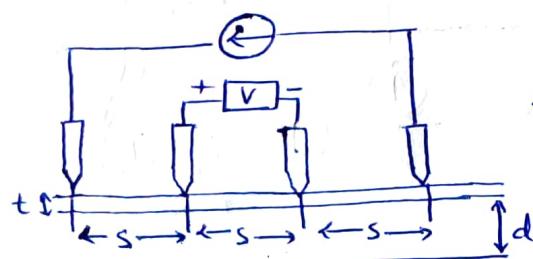
At low resistance, the cable and contact resistance can seriously degrade measurement accuracy. Some ohm-meters have a 'zero adjust' feature, where the test leads are shorted together and the meter is adjusted to zero.

In the four point approach, it is important to keep the voltage contacts very thin so an accurate measurements of L can be made. Voltage probes to avoid "spreading resistance interference"

This spreading resistance is a consequence of the current spreading radially from the probe tip into the sample with a considerable of resistance encountered near the tip. As a rule of thumb, current and voltage probes should be separated by a distance of at least $1.5 \times$ the thickness of the measured sample.

Sample Preparation:- making an accurate resistance measurement requires good electrical contacts to the sample. The minimum spacing b/w voltage and current contacts of $1.5 \times$ the cross sectional perimeter of the sample is recommended, and care should be taken to prevent any alternative conductive path.

Four-point Probe Technique: (Linear measurements)



\Rightarrow fig: In line four point measurement

The two most common approaches for measuring sheet or surface conductivity are the four point probe method and the Van der Pauw method. Both approaches are similar to four-point measurement (for bulk materials) in that current is driven by a pair of probes or connections and the voltage is measured across the other two. The four point probe method is most often realized by contacting a flat film surface with four equally spaced in-lines probes.

The Van der Pauw method can measure resistivity of small, arbitrary shaped layers where the four contacts are typically placed around the periphery of the sample.

The four-point probe method is shown in fig. has four equally spaced in-line probes with probe tip diameters small compared to the probe spacing 's'. An ohmic contact is assumed between the probe tip and the sample current is most commonly passed between the outer two probes, and the voltage difference is measured between the two inner probes. Resistivity in a four-point probe measurement is given by

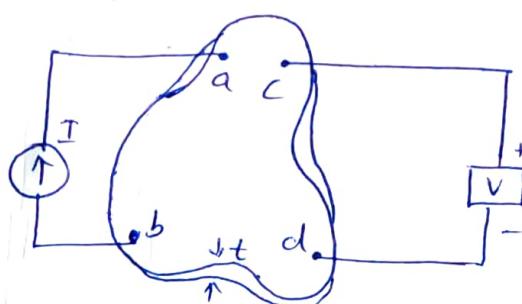
$$\rho = 2ns f V / I$$

Where $f \rightarrow$ correction factor.

The Van der Pauw method can determine the resistivity of small, arbitrarily shaped layers and generally requires less surface area than the four point probe method. It is often used in integrated circuit processing. The method considers four small contacts placed around the periphery of a homogeneous, uniform thickness (t) sample as indicated in figure.

In figure; a resistance $R_{ab,cd}$ is determined by driving a current from point a to b and measuring the voltage from point c to d , or

$$R_{ab,cd} = |V_c - V_d| / I_{ab}$$



and the value of resistivity is given by

$$\rho = \frac{\pi t}{\ln 2}$$

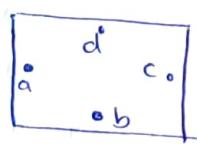
$$\boxed{\rho = 4.532 t R_{ab,cd}}$$

Practical aspect of the method:-

Like the four-point method used for Bulk resistance measurements. Separating the current source from high impedance voltage meter avoids errors associated with contact resistance. Also, when considering Semiconductor measurements, sufficient separation b/w current and Voltage probes is required so that minority carriers injected near the current probes recombine before their presence can be felt at voltage probes. The probes themselves have a tightly controlled spacing, typically $1\text{mm} \pm 0.01\text{mm}$ and the probe tips are individually spring-loaded, to minimize damage to the film surface during probing.

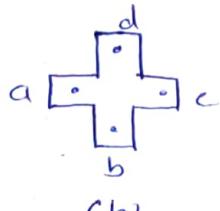
In Van der - Paw measurements, it is common to calculate resistivity from two sets of measurements.

The square pattern shown in fig (a), or a circular pattern with four point equidistant about the periphery, can be made for integrated circuit film measurement "Greek Cross" (fig b) or the clover leaf structure of (fig c) is often used.

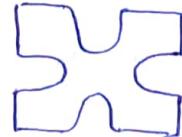


(a)

(Square)



(b) (Greek Cross)



(c)

(clover leaf)

Hot Probe Method:-

A simple method which is widely used to determine the conductivity type of a semiconductor (S.C.) specimen, is the Hot Probe method. Fig shows the schematic of the experimental arrangement. Two fine tungsten probes, made of stainless steel or nickel, are placed on the S.C. Sample and a zero centered galvanometer is connected b/w them. One of the probe is kept at room temperature, and other is heated to about 80°C . It is convenient to use a miniature soldering iron tip as the hot probe.

The hot probe heats the semiconductor immediately beneath it so that the kinetic energy of free carriers in this region is increased. Therefore, the carriers diffuse out of the hot region at a faster rate than they diffuse into this region from the adjacent low-temperature regions. If the SC is n-type, electron will move away from the hot probe leaving a positive charge region of donors; and the hot probe becomes positive with respect to the cold probe. The current then will flow from the hot probe to the cold probe. In a p-type S.C., the direction of current flow is reversed; thus the polarity of hot probe indicates whether the S.C. is n or p-type.

The hot probe method is not applicable to S.C. in which the electron and hole concentrations are nearly equal. In such a case any material that has a higher electron mobility will always be identified as n-type.

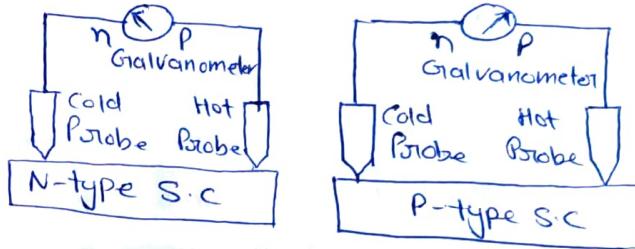


Fig: Hot Probe Method.

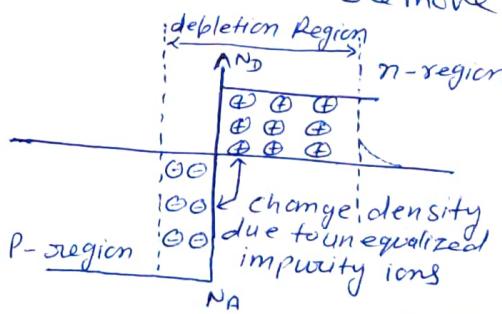
Capacitance - Voltage measurement:

The Capacitance - Voltage measurement is used to determine the majority carrier concentration in S.C. as a function of distance (depth) from the junction. The C-V measurement can quantitatively describe the free carrier concentration together with information about traps. Defects appearing as traps at energies deep within the forbidden gap of a S.C. can add or remove free carriers.

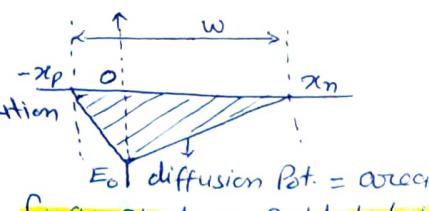
Principle of the method:

The capacitance at a P-n junction depends on the properties of the charge depletion layer formed at the junction. Fig(a) shows a abrupt Pn junction and it is depleted of free carriers.

Fig(b) shows the electric field distribution in equilibrium condition for charge neutrality. The difference in energy



Fig(a) Charge density



Fig(b) Electric field distribution

between conduction bands fig (c) as one crosses the PN junction is called the diffusion potential V_{bi} (built-in potential). To calculate the electric field distribution within the transition region, we begin with Poisson's equation.

$$\frac{\partial E}{\partial x} = \frac{q}{\epsilon} [P-n + N_D^+ - N_A^-] \rightarrow (1)$$

for regions predominately doped n-type

$$\frac{\partial E}{\partial x} \approx \frac{q}{\epsilon} N_D^+ \quad \text{for } 0 < x \leq x_n \rightarrow (2) \quad [\text{neglecting the contribution of carriers (P-n)}]$$

for doped P-type region

$$\frac{\partial E}{\partial x} = \frac{q}{\epsilon} N_A^- \quad \text{for } -x_p \leq x < 0 \rightarrow (3)$$

The value of max electric field E_0 can be found by integrating either eqn (2) or eqn (3) with appropriate limit.

$$\int_{E_0}^0 dE = \frac{q}{\epsilon} N_D^+ \int_0^{x_n} dx, \quad 0 < x < x_n \rightarrow (4)$$

or

$$\int_0^{E_0} dE = \frac{q}{\epsilon} N_A^- \int_{-x_p}^0 dx, \quad -x_p \leq x < 0 \rightarrow (5)$$

Therefore the maximum value of the electric field is

$$E_0 = -\frac{q}{\epsilon} N_D^+ x_n = -\frac{q}{\epsilon} N_A^- x_p \rightarrow (6)$$

Since the electric field at any distance x , is the negative of the potential gradient at that point

$$E(x) = -\frac{\partial V}{\partial x}$$

$$\text{or } -\int_0^{V_{bi}} \frac{\partial V}{\partial x} = \int_{-x_p}^{x_n} E(x) dx \rightarrow (7)$$

Thus, the negative of the contact potential is simply the area under the $E(x)$ vs x triangle, this relates the contact potential to the width of the depletion region

$$V_{bi} = -\frac{1}{2} E_0 W = \frac{1}{2} \frac{q}{\epsilon} N_D^+ x_n W \rightarrow (8)$$

Since from eqn (6), $N_D^+ x_n = N_A^- x_p$ and

$$W = x_p + x_n$$

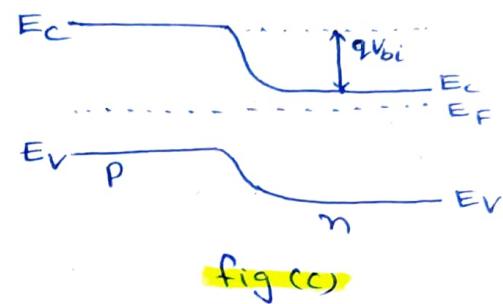


fig (c)

We can write

$$x_n = \frac{WN_A^-}{N_A^- + N_D^+}$$

Put in eqn (8) \Rightarrow

$$V_{bi} = \frac{1}{2} \frac{q}{\epsilon} \frac{N_A^- N_D^+}{N_A^- + N_D^+} W^2 \quad \rightarrow (9)$$

By solving for W

$$W = \left[\frac{2\epsilon V_{bi}}{q} \left(\frac{N_A^- + N_D^+}{N_A^- N_D^+} \right) \right]^{\frac{1}{2}}$$

$$W = \left[\frac{2\epsilon V_{bi}}{q} \left(\frac{1}{N_A^-} + \frac{1}{N_D^+} \right) \right]^{\frac{1}{2}} \quad \rightarrow (10)$$

We can also calculate the penetration of the transition region into the n and p materials.

$$x_p = \frac{WN_D^+}{N_A^- + N_D^+} = \frac{W}{1 + \frac{N_A^-}{N_D^+}} = \left\{ \frac{2\epsilon V_{bi}}{q} \left[\frac{N_D^+}{N_A^- (N_A^- + N_D^+)} \right] \right\}^{\frac{1}{2}} \quad \rightarrow (11)$$

$$x_n = \frac{WN_A^-}{N_A^- + N_D^+} = \frac{W}{1 + \frac{N_D^+}{N_A^-}} = \left\{ \frac{2\epsilon V_{bi}}{q} \left[\frac{N_A^-}{N_D^+ (N_A^- + N_D^+)} \right] \right\}^{\frac{1}{2}} \quad \rightarrow (12)$$

The depletion width will widen under applied reverse bias, $-V_R$ and V_{bi} must be replaced by $(V_{bi} - V_R) > V_{bi}$.

We are now able to calculate the capacitance of the depletion region assumed to be a parallel-plate capacitor of plate separation W and area A .

$$C = \frac{\epsilon A}{W} = \frac{\epsilon A}{\left[\frac{2\epsilon}{q} \left(\frac{N_A^- + N_D^+}{N_A^- N_D^+} \right) (V_{bi} - V_R) \right]^{\frac{1}{2}}} \quad \rightarrow (13)$$

I-V characteristics of diode:-

The current-voltage measurement technique is used both for the design of SC devices and for yield or process checks during manufacture.

The ideal diode equation, for the current density can be given by the equation

$$J = q \left(\frac{D_n}{T_n} n_p + \frac{D_p}{T_n} p_n \right) \left(e^{\frac{qV}{kT}} - 1 \right) \quad \rightarrow (1)$$

Where

D_n, D_p = electron and hole diffusion constant

n_p, p_n = equilibrium electron and hole concentration in n and p regions

$L_n, L_p \rightarrow$ Debye lengths for e^- and holes

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$V_J \rightarrow$ Junction diode

more generally eqn (1) \Rightarrow

$$J = J_0 (e^{\frac{qV_J}{nKT}} - 1) \quad \text{---(2)}$$

$$\text{or} \quad J = J_0 \left[\exp \left(\frac{q(V_J - IR)}{nKT} \right) - 1 \right] \quad \text{---(3)}$$

The applied voltage $V_A = V_J + IR \approx V_J$ for low currents, where R is the extrinsic diode resistance. The first term dominates for positive applied voltage (forward bias junction) several times greater than kT , and the current increases exponentially. The second term dominates for negative applied voltage (reverse bias junction) several times greater than kT , and the reverse current approaches a constant value $-J_0$.

When recombination in the depletion region is taken into account, the current density can be given by the formula:

$$J = J_0 \left[\exp \left(\frac{qV_J}{nKT} - 1 \right) \right] + \frac{q n_i w}{2 \tau_0} \left[\exp \left(\frac{qV_J}{nKT} \right) - 1 \right] \quad \text{---(4)}$$

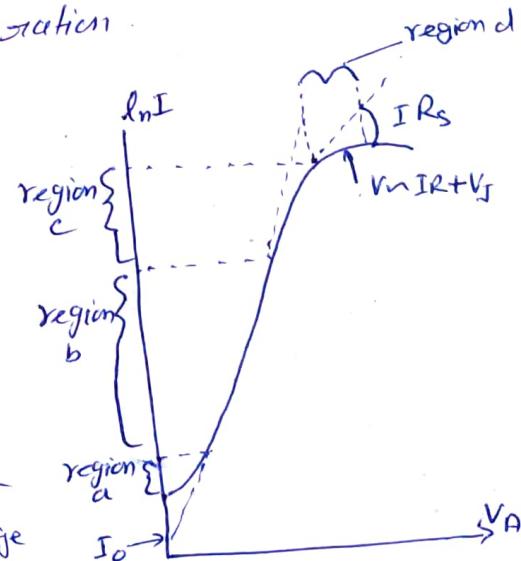
where $w \rightarrow$ depletion width

$\tau_0 \rightarrow$ effective life time

$n_i \rightarrow$ intrinsic carrier concentration

In forward biasing, the exponential term dominates at very low positive V_J , the second term can dominate for semiconductors with small n_i (band gap $E_g \gg 1\text{ eV}$). This comes out because J_0 is proportional to n_i^2 .

This is illustrated in fig 1. Where the logarithm of current is plotted vs Voltage and region (a) shows an inverse logarithm slope of $2kT/q$. At higher V_J , the inverse slope approaches the ideal kT/q value in region (b) but again deviates at higher bias in region (c).



Deviation from the ideal forward bias P-N junction

I-V Characteristic

The current in region (c) has been attributed to effects of higher injected minority carriers approach the same concentration as the majority carriers.

The net result is an increase in recombination with an exponential slope of $2kT/q$.

Deep-Level Transient Spectroscopy (DLTS):-

The identification and control of defects have always been among the most important and crucial tasks in materials and electronic device development. Deep level transient Spectroscopy (DLTS) probe; the temperature dependence of charge carriers escaping from trapping centers formed by point defects in the materials. This technique is able to characterize each type of trapping centers by providing the activation energy of defect level relative to one of energy band edges and capture cross section of the traps. It can also be used to computation and depth profile of the trapping centers.

Deep level Transient Spectroscopy is not able to determine the chemistry or the origin of a defect. DLTS data should therefore be used in conjunction with the techniques.

Principle of Deep Level Transient Spectroscopy:-

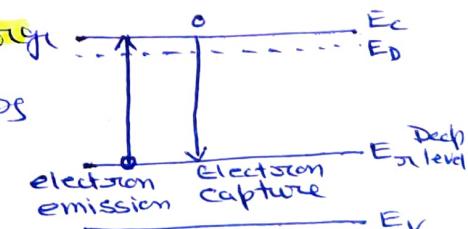
The basic of this method is dependence

of the capacitance of a space charge region on the occupancy of the traps

Within the space charge region in

a.s.c. Under a non-equilibrium condition

such as that existing in a space charge region, a trapped carrier can escape from a trapping center by thermal excitation to the nearest energy band.



In a PN junction, a space charge region is formed by the reverse biasing the PN junction. The diode is initially reverse biased to empty the traps. When the bias across the junction is reduced (or even forward biased), the width of the space charge region is reduced. An equilibrium condition is established in the neutralized region with the majority carriers populating the traps.

When the reverse bias is restored, the space charge region is again created as before, with the only difference being that there are trapped carriers now residing in the defect centers within the space charge region. The non-equilibrium condition thus created causes the trapped carriers to be thermally reemitted to the relevant energy band. The rate of thermal emission or detrapping of a carrier is temperature dependent. The change of the occupancy of these trapping centers is reflected in the capacitance of the junction producing a capacitance transient. The trap concentration can be determined from the intensity of the capacitance peak, and the polarity of the carriers can be found from the sign of the capacitance change.

Instrumentation of DLTS:- A first DLTS experimental set-up was reported by long and its popularity known as Boxcar technique. A block diagram of basic DLTS spectrometer is shown in fig. The high frequency capacitance meter measures the capacitance across junction device and typically has a 1 MHz test frequency. A pulse generator with variable pulse width and pulse height as well as variable d.c offset bias is required to provide a steady state or quiescent

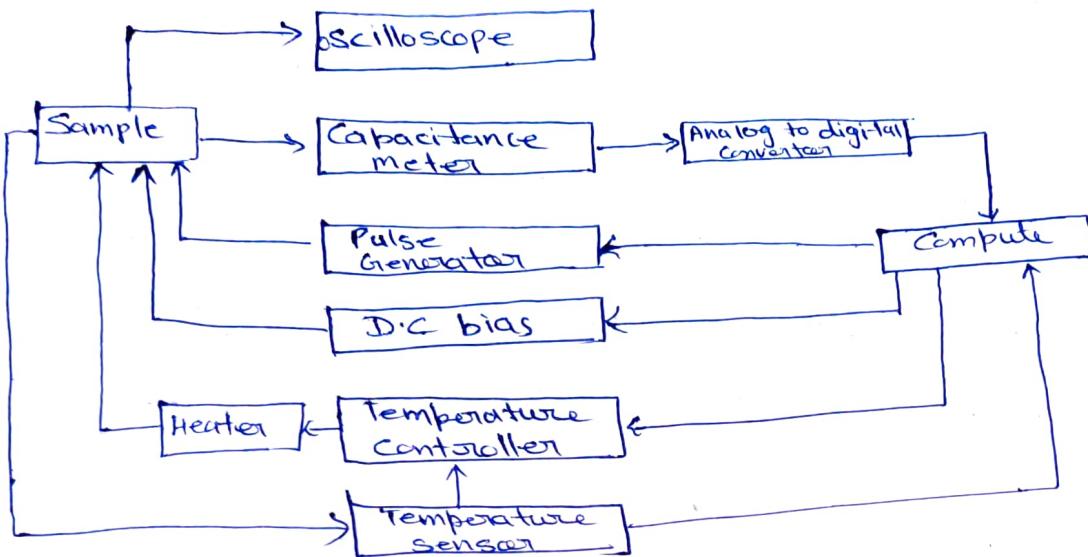


Fig:- A DLTS spectrometer using a Boxcar technique

reverses bias as well as the trap-filling pulse. A standard dc power supply can also be used instead of dc bias offset bias of the pulse generator. An analog-to-digital converter is needed to digitize the analog output of the capacitance meter. It is also helpful to have an oscilloscope to visually monitor the capacitance transient. Poor or degraded contacts on the sample can give a noisy or spurious signal, and an oscilloscope is a good diagnostic tool for detecting any problem.

A computer is necessary for data collection, analysis and archiving. A wide temperature range (77 to 380 K) is required to detect the trapping levels from near the energy band edges to middle of the band gap.

Therefore a temperature controller would be helpful for precise temperature control.