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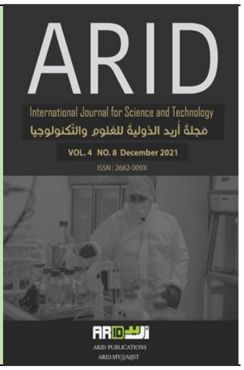

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Electrical Properties of GaAs Implanted with High Energy (100meV) ^{28}Si and ^{120}Sn Ions

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الصفات الكهربائية لزرنيخ الجاليوم المقذوف بطاقة عالية (100 مليون إلكترون فولت) بأيونات السيليكون والقصدير

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Abstract

Single crystal n-GaAs substrates have been implanted at 300 K with 100 MeV ^{28}Si and ^{120}Sn ions to a dose of $1x10^{18}$ions/m^2 independently. The electrical properties of these samples has been investigated and compared after implantation and annealing up to 850 °C by current voltage (I-V) measurements. It has been observed that the I-V curves for the samples implanted with ^{28}Si ions show p-n junction like characteristics which then show a linear I-V characteristics for the annealing treatment between 150-550 °C. Annealing the samples at 650 °C results in a typical diode like I-V characteristics which become less non-linear after further annealing at 750 °C. Further annealing at 850 °C results in to a back ward diode like behavior. However the I-V curves for the samples implanted with ^{120}Sn ions and annealed up to 450°C were linear which then show a weak non linearity for the annealing treatments between 550°C-750°C. After 850°C annealing the samples show a strong nonlinearity typical of a p-n junction. The temperature dependence of resistance of both ^{28}Si and ^{120}Sn implanted GaAs samples after implantation and different annealing steps are investigated and the possible conduction mechanisms are discussed.

Keywords : GaAs , MeV Ion implantation, I-V curves , Defects in crystals. Electrical conduction

الملخص

يهدف هذا البحث إلى دراسة الصفات الكهربائية لبلورات الزرنيخ الجاليوم بعد تعرضها للانغراس الأيوني بطاقة عالية جدا (100 مليون إلكترون فولت) بأيونات السيليكون والقصدير بشكل مستقل.

قذفت بلورات أحادية، من نوع سالب من مركب زرينخيد الجاليوم بأيونات سيليكون وأيونات قصدير بطاقة عالية مقدارها 100 مليون إلكترون فولت. بجرعة مقدارها 1* 10^{18} أيون لكل متر مربع عند درجة حرارة الغرفة. تم دراسة ومقارنة السلوك الكهربائي للبلورات المقذوفة بدراسة منحنى التيار – جهد بعد القذف وكذا بعد تعرضها لعملين التلدين الحراري عند درجات حرارة مختلفة حتى 850 درجة مئوية. لوحظ أن منحنى التيار – جهد للبلورات التي قذفت بأيونات السيليكون أبدت سلوكا يشبه سلوك الوصلة الثنائية، ثم سلكت السلوك الخطي بعد تعرضها للتلدين الحراري ما بين درجات الحرارة (150 – 550 درجة مئوية) وبعد تلدينها إلى درجة حرارة 650 درجة مئوية أظهرت هذه العينات ثانية سلوك الوصلة الثنائية، وعند زيادة درجة حرارة التلدين إلى 850 درجة مئوية بدأ يختفي سلوك الوصلة الثنائية ليظهر سلوك يشبه الوصلة الثنائية العكسية. بالمقابل أظهرت منحنيات التيار – جهد للعينات المقذوفة بأيونات القصدير سلوكا خطيا بعد عملية الانغراس الأيوني وظلت محتفظة بهذا السلوك بعد تعرض العينات للتلدين الحراري حتى 450 درجة مئوية، ثم أظهرت سلوكا غير خطي ضعيف عند التلدين بدرجات حرارة بين 550 – 750 درجة مئوية، وبزيادة درجة حرارة التلدين إلى 850 درجة مئوية أظهرت العينات سلوك الوصلة الثنائية في منحنيات التيار – جهد. تمت دراسة تأثير درجة الحرارة على مقاومة العينات المقذوفة بكل من السيليكون والقصدير بعد الانغراس الأيوني مباشرة، وكذا العينات التي لدنت حراريا وذلك بقياس مقاومة العينات من خلال منحنيات التيار- جهد عند درجات الحرارة المختلفة. تمّ دراسة سلوك العينات بدراسة آليات التوصيل الكهربي التي تسيطر على السلوك الكهربي لهذه العينات.

الكلمات المفتاحية: زرنيخيد الجاليوم، الانغراس الأيوني ذو الطاقات العالية، منحنيات التيار- جهد، أعطاب البلورات، التوصيل الكهربي.

1. Introduction:

Ion implantation in III-V compound and especially in GaAs has become a well-known procedure for device technology [1, 2]. In recent years high energy ion implantation has attracted considerable attention as a tool for fabrication of special device structures, which require deep conductive layers [3, 4]. Many of these devices are sensitive to electrically active defects and therefore the investigations of defects produced by high energy ion implantation and effect of annealing on their electrical characteristics are desirable. As such, the defect creation and the annealing process for MeV implantation seems to be more complicated than that for conventional implantation [5]. The objective of this paper is to understand and compare the change in the electrical characteristics of n-GaAs substrates due to radiation defects associated with high energy implantation of ^{120}Sn and ^{28}Si ions, and the effect of annealing on their electrical behaviour.

2. Experimental Details:

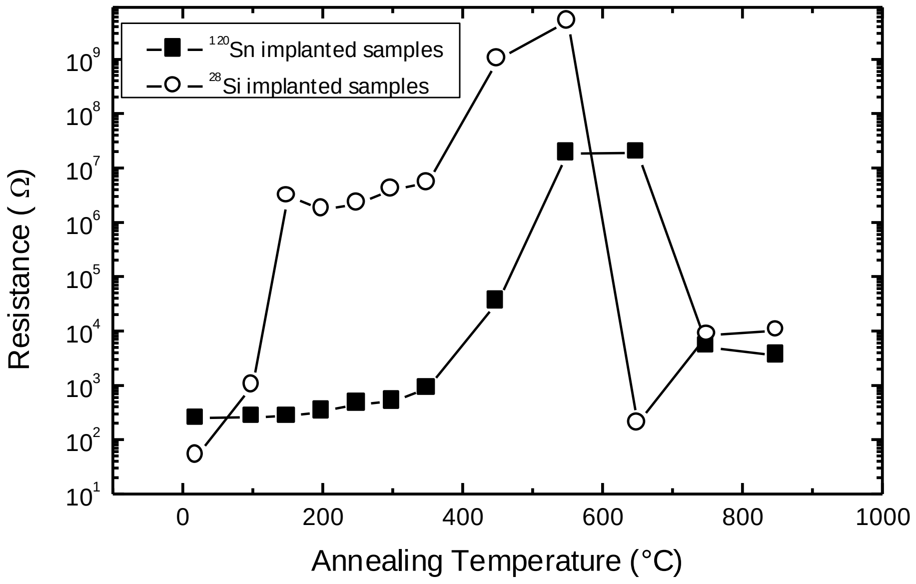
The samples used in this experiment were mirror polished <100> n-GaAs substrates with background doping concentration of 2×10^{22} m^{-3} having an area of 7 mm x 7mm and thickness of 400 μm. All the Samples were carefully cleaned then immediately loaded into the target chamber connected to one of the beam lines of the NEC 16 MV Pelletron accelerator [6] at Nuclear Science Centre, India. Cleaning procedure of the samples has been described elsewhere [7]. The energy of implantation for the samples implanted with ^{120}Sn ions and ^{28} Si ions was 100 MeV. All samples implanted at room temperature, and with a total implanted dose of $1x10^{18}$ ions/m^2. During implantation the beam current was held at 1-5 particle Nano ampere (pnA) and the ion beams were scanned over the full sample surface. The samples were oriented at an angle of 7° with respect to the beam axis so as to minimize the channeling effect. The implanted samples were isochronally annealed for 10 minutes at different temperatures in the range of 100-850 °C in high purity hydrogen ambient. To prevent the out diffusion of As from the GaAs surface during the annealing process at high temperature, the implanted samples were capped with a clean polished piece of unimplanted n-GaAs of the same size with the polished surface in contact. The unimplanted samples were used as reference samples to monitor any change in the electrical properties due to degradation during annealing process.

The electrical measurements have been done by fabricating ohmic contacts of small area dots on the front of the sample and large area contacts on the back of the surface. The back contacts were made by evaporating a uniform coating of Au-Ge-Ni alloy. The top contacts were made by evaporating Au-Ge-Ni dots of area 0.0045 cm2 through a metal mask. The Au-Ge-Ni contacts was then alloyed at 450 °C in hydrogen ambient for one minute to form ohmic contacts. The ohmic contacts were made before implantation for those samples to be annealed at temperatures less than 450 °C. The Current voltage (I-V) measurements were carried out over a temperature range 100-473 K by using a programmable voltage source, a Keithley digital electrometer and a variable temperature cryostat.

3. Results and Discussion:

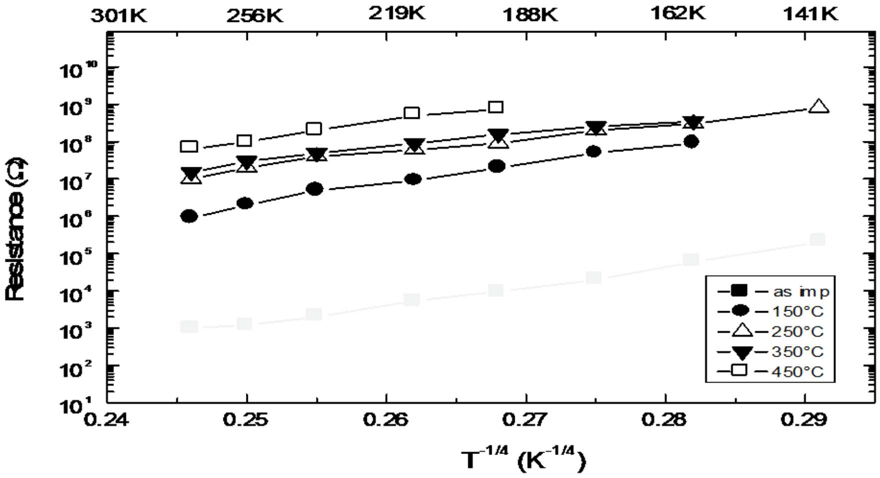
Current voltage (I-V) characteristics for the ^{28}Si and ^{120}Sn implanted samples before and after annealing have been measured. We find that for the samples implanted with ^{28}Si ions the I-V curve for the as-implanted sample shows a highly non-linear diode like behaviour. After annealing at 100 °C the characteristics become weakly non-linear. The samples annealed between 150°-550 °C show a fairly linear I-V characteristics. The samples annealed at 650°C again show a non-linear diode like I-V characteristics. Annealing of the sample to 750 °C produces a leaky diode-type I-V behaviour. After annealing the sample to 850 °C the samples shows a backward diode like I-V characteristics. On the other hand, for the samples implanted with ^{120}Sn ions, the I-V characteristics of the as implanted samples and samples annealed up to 450 °C are linear. Further annealing of the samples to 550 °C and 650 °C shows a weak non linearity which increases considerably as the annealing temperature increase to 750 °C. After 850 °C annealing, the samples show p-n junction like behaviour. The I-V curve of the unimplanted sample remains ohmic and does not show any significant change of resistance due to annealing treatment. This suggests that there is no degradation of the material and the complex I-V characteristics are therefore attributed to the defects in the implanted layers.

In order to understand the complex behaviour of the as implanted and annealed samples, we estimate the equivalent effective series resistance from various linear and nonlinear I-V curves. For weakly and strong nonlinear I-V characteristics the effective series resistance is estimated from the high current region where the series resistance is dominating.

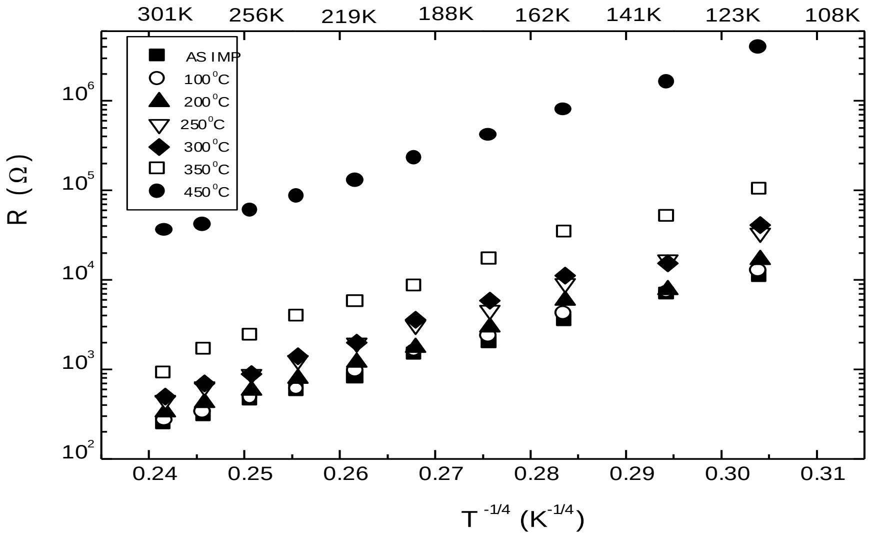


Figure(1): Room temperature resistance of the as-implanted sample and samples annealed at different temperatures for samples implanted with ^{28}Si and ^{120}Sn ions.

Fig.1 shows room values of effective resistance as measured above for different annealing temperatures for both ^{28}Si and ^{120}Sn implanted samples. It has been observed that for the samples implanted with ^{28}Si ions, the room temperature resistance of the as implanted sample is about 50 Ω, which increase with increasing annealing temperature and reaches a maximum values of about 5×10^{9} Ω at 550 °C. Further annealing at 650 °C, causes a drastic decrease in the resistance value to 200 Ω which again increases to about 10^{4} Ω after annealing at 850 °C. The effective resistance of the GaAs samples implanted with ^{120}Sn ions is 2.5×10^{2} which increase with an increase in annealing temperature and reaches a value 2×10^{7} Ω for the sample annealed at 650°C. However, the samples annealed at temperatures higher than 650°C show a reduction in their resistance values and reaches a value of 3.5×10^{3} Ω for the sample annealed at 850°C. It has been observed that for the samples implanted with ^{28}Si ions there is an annealing stage occur between room temperature and 150 °C, which is not observed for the samples implanted with ^{120}Sn ions. This suggests that for the samples implanted with heavy ^{120}Sn ions a large defects concentration that are responsible for the p-n junction like behaviour in the case of Si implanted samples before the first annealing stage may be annealed by bulk annealing during implantation. The p-n junction like behaviour for the as implanted samples with ^{28}Si ions indicating a p-type conductivity of the implanted region. Some investigations involving high dose proton and neutron irradiation suggest that the irradiated layers are p-type [8] Temperature dependence of resistance of the as-implanted sample and the samples annealed at different temperatures are examined next. It is observed that for the samples implanted with ^{28}Si and ^{120}Sn ions the as implanted sample and the sample annealed up to 450°C satisfy the relation $\log R \propto T^{-1/4}$ in the temperature range (110 K-270 K) as shown in Fig. 2 and Fig. 3. respectively.



Figure(2): Resistance vs. $T^{-1/4}$ of the samples implanted with ^{28}Si ions and annealed at various temperatures up to 450 °C.



Figure(3): Resistance vs. $T^{-1/4}$ of the samples implanted with ^{120}Sn ions and annealed at various temperatures up to 450 °C.

These observations suggest that up to 450°C annealing, there remains large concentration of defect states in the implanted samples. As a result, the conductivity mechanism of these samples in the low temperature range is dominated by variable range hopping between defect energy levels in the forbidden gap and the result may be described by [9]:

$$\rho = \rho_0 \exp\left(T_0/T\right)^{1/4} \qquad (1)$$

The values of T_0 are obtained from the slopes of log R vs. $T^{-1/4}$ curve and are given in Table I. We can estimate the localized states density at Fermi level $N(E_F)$ according to[10]:

$$N(E_F) = (C^4\alpha^3 / T_0 k) \qquad (2)$$

where $C^4 \cong 20$, $\alpha(cm^{-1}) = (2m^*/\hbar^2)^{1/2}(E_g/2)^{1/2}$ is the attenuation distance of the

wave function for the localized state, E_g is the band gap and m* is the effective mass of the electron. The values of N (E_F) for the as-implanted sample and the samples annealed at temperatures up to 450°C are listed in Table I and can be assigned to the vacancy clusters. It is observed that for both ^{120}Sn and ^{28}Si implanted samples the $N(E_F)$ values decrease with the increase in the annealing temperature indicates that the high concentration of these defect states decreased with the increase in annealing temperature.

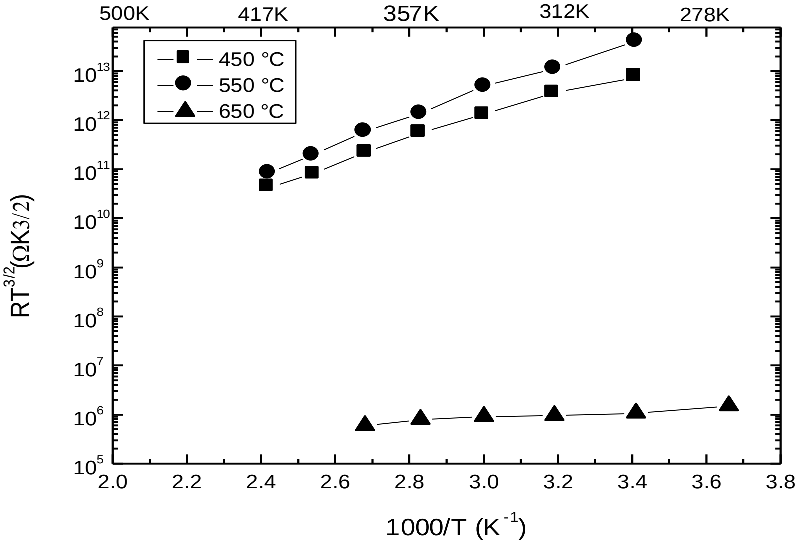
It is observed that value of $N(E_F)$ at room temperature for samples implanted with Si ions is large as compared to that of the samples implanted with Sn ions. The values of N (E_F) for the Si implanted samples after 150 °C annealing are comparable to N (E_F) at room temperature for the GaAs samples implanted with ^{120}Sn ions. This supports our previous speculation that some of the defect states are annealed during the implantation of heavy ^{120}Sn ions. It is also observed that the defect density of states at fermi level after

Table(I): T_0 values and corresponding $N(E_F)$ of the samples implanted with ^{28}Si and ^{120}Sn ions for different annealing temperatures:

Samples implanted with ^{28}Si ions			Samples implanted with ^{120}Sn ions		
Annealing Temperature (°C)	$T_0 x 10^7$ (K)	$N(E_F) x 10^{19}$ ($cm^{-3}.eV$)	Annealing Temperature (°C)	$T_0 x 10^7$ (K)	$N(E_F) x 10^{19}$ ($cm^{-3}.eV$)
As- implanted	0.137	293	As- implanted	1.288	3.11
150	1.200	3.34	100	1.336	3.00
200	1.494	2.68	200	1.342	2.99
250	1.797	2.23	250	1.859	2.16
300	1.832	2.20	300	1.992	2.01
350	2.345	1.71	350	2.507	1.60
450	6.990	0.574	450	2.952	1.36

annealing to 450 °C is larger in the samples implanted with ^{120}Sn ions than samples implanted with ^{28}Si ions. The departure from $T^{-1/4}$ behaviour for the samples annealed at temperatures higher than 450°C for both ^{120}Sn and ^{28}Si implanted samples suggests that the high concentration of the damage states is annealed and the tunnel assisted hopping conduction mechanism between the defect states at low temperatures no longer exists.

Next we shall consider the temperature dependence of the resistance for the samples annealed between 450-850 °C in the measurement temperature range of 300-470 K. It is observed that the samples implanted with Si ions and annealed between 450-650 °C satisfy the relation $\log (RT^{3/2}) \propto T^{-1}$ in the as shown in Fig. 4. This is possibly because

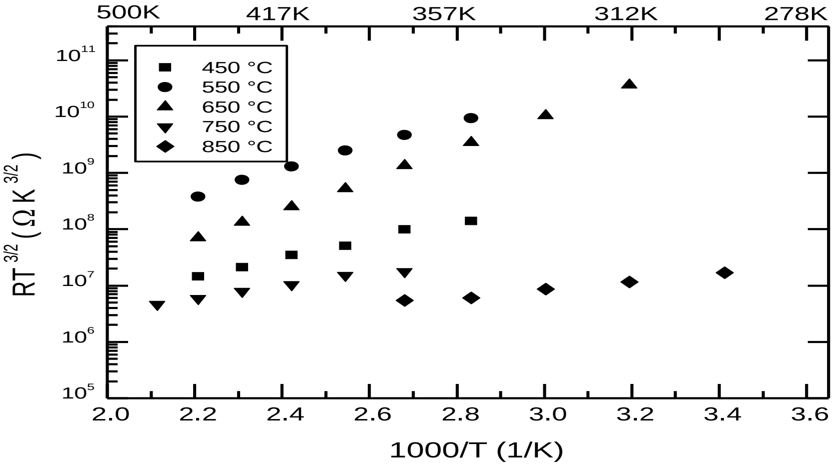


Figure(4): $RT^{3/2}$ vs. 1/T of the samples implanted with ^{28}Si ions and annealed at various Temperatures up to 650 °C.

of the electrical transport in this temperature region being dominated by carriers in the extended states for which the resistivity of the sample can be expressed by [11]:

$$\rho(T) = \frac{1}{N^* T^{3/2} q \mu(T) \exp\{-(E - E_F)/kT\}} \qquad (3)$$

where, $N^* = 2\{2\pi m_n{}^{2}\}^{3/2}$, m_n is the effective mass of the charge carrier, E is the energy of the band edge, μ is the mobility, q is the electron charge, E_F is the Fermi energy, T is the absolute temperature, k is the Boltzman's constant and $\hbar$ is the Planck's constant. The $(E - E_F)$ values of these samples are calculated from slopes of the plots of log $(RT^{3/2})$ vs. 1/T and listed in table II. The $(E - E_F)$ values for the samples annealed at 450°C is 0.47 eV and reach 0.54 eV for the samples annealed at 550 °C. Further increase of the annealing temperature to 650 °C, $(E - E_F)$ value decrease to 0.10 eV. Similar electrical transports have been observed for the samples implanted with ^{120}Sn ions and annealed between 450- 850 °C and shown in Fig. 5.



Figure(5): $RT^{3/2}$ vs. 1/T of the samples implanted with ^{120}Sn ions and annealed at various temperatures up to 850 °C.

Table(II): ($E-E_F$) of the samples implanted with ^{28}Si and ^{120}Sn ions for different annealing temperatures:

Samples implanted with ^{28}Si ions		Samples implanted with ^{120}Sn ions	
Annealing Temperature (°C)	($E-E_F$) (eV)	Annealing Temperature (°C)	($E-E_F$) (eV)
450	0.47	450	0.36
550	0.54	550	0.42
650	0.10	650	0.56
-	-	750	0.24
-	-	850	0.17

The ($E-E_F$) calculated from slopes of the plots of log ($RT^{3/2}$) vs. 1/T for these samples are listed in table II. These values range from 0.36 eV for 450 °C annealed samples and increased to 0.42 eV after annealing to 550 °C, and reach 0.56 eV for samples annealed at 650 °C. At higher annealing temperatures, ($E-E_F$) decreases with annealing temperature such that the ($E-E_F$) for 850 °C annealing sample is 0.17 eV.

It is clear that the annealing behaviour of the samples implanted with ^{28}Si and ^{120}Sn ions are complex, but the general nature of the electrical characteristics is somewhat similar. However the samples implanted with ^{120}Sn ions requires higher annealing temperature to attain similar characteristics of the samples implanted with ^{28}Si ions. The samples implanted with ^{28}Si ions and annealed at temperature higher than 650 °C did not satisfy the relation log ($RT^{3/2}$) $\propto$ T^{-1}.This suggests that the implanted region still consists a large concentration of the defect complexes and the annealing treatment for these samples modify the electrical transport due to the modification of the defect structure. More understanding is required to understand the behaviour of these samples. Therefore an annealing up to 850 °C does anneal out the entire defect states for both ^{120}Sn and ^{28}Si implanted samples and higher annealing temperatures are required for the recovery of the residual defects.

4. Conclusions:

We have implanted ^{120}Sn and ^{28}Si ions in single crystal n-GaAs substrates at energy of 100 MeV respectively. The I-V curves at room temperature for the as implanted samples and samples annealed up to 850 °C show a series of complex behaviour. We have tried to understand this complex electrical behaviour by measuring the resistance of the samples as a function of temperature in the temperature range 100-433 K for the as implanted sample and after annealing at different temperatures. The temperature dependence of both ^{28}Si and ^{120}Sn as-implanted samples and the samples annealed upto 450°C seems to follow variable range hopping conduction at low temperatures (100 K-270 K). At room temperature and above the samples implanted with Si ions and annealed between 450-650 °C, and for the ^{120}Sn implanted samples and annealed between 450-850 C is dominated by carriers in the extended states.

The annealing behaviour of the samples implanted with ^{28}Si and ^{120}Sn ions are complex, but the general trend of the electrical characteristics is somewhat similar. However the samples implanted with ^{28}Si ions requires lower annealing temperature to attain similar characteristics of the samples implanted with ^{120}Sn ions.

Annealing up to 850 °C does anneal out the entire defect states for both ^{120}Sn and ^{28}Si implanted samples and higher annealing temperatures are required for the recovery of the residual defects. The annealing treatment to higher temperatures by using rapid annealing processes or laser pulse processes is required to make the defects either to become stable or to anneal out, which will give a permanent electrical property to the materials under investigations and qualifies them for electronic devices requiring deep conducting or insulating layers.

List of Abbreviations:

GaAs	Gallium arsenide
μm	Micron
^{28} Si	Silicon
^{120}Sn	Tin
MeV	Million electron volt
I	Current
V	Voltage
R	Resistance
T	Absolute Temperature
ρ	Resistivity
μ	mobility
m_n	Effective mass of the charge carrier
q	Electron charge
E_F	Fermi energy
E	Energy of the band edge (conduction or valance)
$N(E_F)$	Localized states density at Fermi level
α	Attenuation distance of the wave function for the localized state
$\hbar$	Planck’s constant
k	Boltzmann's constant

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