Deep Levels in Semi-Insulating GaAs : Cr and Undoped GaAs

(SI GaAs : Cr과 Undoped GaAs의 깊은 준위)

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要 約

광 유도 전류 천이 (photo-induced current transient) 방법으로 측정한 SI GaAs의 전자와 정공 trap이 갖을 수 있는 activation energy(ΔE_T)의 범위는 0.16±0.01eV에서 0.98±0.01eV까지 분포되어 있다. SI Undoped GaAs가 SI GaAs : Cr 보다 깊은 준위의 수가 적음을 확인 하였다. Trap의 열적인 capture cross section과 농도를 평가 하였고, 약간의 trap은 SI GaAs 성장시에 발생될 수 있는 결함과 관련되어 있음을 확인하였다. 특히 SI GaAs에서 보상 level로 작용하는 Cr과 "0" level를 좀 더 정확하게 측정하기 위하여 서로 다른 측정방법을 사용하여 측정한 결과를 각기 비교 검토 하였다. 즉, PICT측정, 상온 이상의 온도에서 측정한 Hall data 및 광전류 spectra data 등을 비교 검토 하였으며, 보상 level은 격자 결합이 매우 약함을 확인할 수 있었다. Hall data를 computer로 분석한 결과 중성 불순물 scattering이 측정 온도 범위에서 매우 중요한 역할을 하고 있음을 알 수 있었다.

Abstract

Electron and hole traps in semi-insulating GaAs with activation energies ΔE_T ranging from 0.16 ± 0.01 to 0.98 ± 0.01 eV, have been detected and characterized by photo-induced current transient measurements. SI undoped GaAs has fewer deep levels than SI GaAs: Cr. The thermal capture cross section and density of the traps have been estimated and some of the centers have been related to native defects. In particular, the activation energy of the compensating Cr, and "O" levels in semi-insulating GaAs were accurately measured. The transient measurements were complemented by Hall measurements at T > 300K and photocurrent spectra measurements. The transition energies for the deep compensating levels obtained by the analyses of data from these measurements, when compared with those from the transient measurements, indicate negligible lattice-coupling of these centers. Analysis of the transport data also indicates that neutral impurity scattering plays a significant role in semi-insulating materials at high temperatures.

I. Introduction

The fabrication of reliable GaAs Field Effect Transistors (FETs) and other microwave devices requires the availiability of high quality semi-insulating (SI) substrate materials. Most of the recent investigations [1,2,3] on SI GaAs have been directly related to the electrical and optical properties of the Cr compensating levels, which act as deep acceptors, in these materials. In addition to the known properties of the Cr levels in SI materials[4], it is important to determine the

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thermal emission properties of levels, viz., their activation energies and capture cross sections for electrons and holes.

Deep level defects in SI GaAs, including the compensating Cr related level, were detected and characterized in this study by the Photo-Induced Current Transient (PICT) measurement technique, first reported by Hurtes et al. [5] This technique has to be employed since it is not possible to perform conventional capacitance transient or Deep Level Transient Spetroscopy (DLTS) measurements with Schottky barriers fabricated on materials exhibiting high resistivity. The nature of the traps were inferred by performing the PICT experiments with intrinsic and extrinsic monochromatic excitation. The energy position of some of the more dominant defects levels were also obtained from the variation of the photocurrent with incident photoexitation energy and from analyses of these spectra. The transport parameters in the semi-insulating materials were measured at high temperatures using the van der Pauw technique[6] The variation of resistivity, Hall mobility and Hall cofficient with temperature, for $T > 350K$, were determind. The mobility data were analyzed taking into account the relevant scattering mechanisms. The compensation in the materials and other important transfort parameters were determined from a solution of the change neutrality equations. This equations were appropriately derived for the materials under consideration.

II. Theoretical Consideration

1. PICT

Excess carriers can be generated by optical excitations and some of them may be trapped at the deep centers. Subsequent thermal emission of the trapped carriers in the dark is then monitored as a function of temperature by Photo-Induced Current Transient (PICT) measurements. The current change after the photoexitation is switched off can be expressed by [5,7]

$$i(t) = K\{e_n n_T(t) + e_P[N_T - n_T(t)]\} \qquad (1)$$

where the constant K includes the geomaterial parameters of the device and the penetration depth of the light pulse, the concentration of trapped electrons, and N_T the total trap density. Assuming an exponential emission, the measured transient current is then given by

$$\Delta i(t) = K(e_n - e_P)[n_T(0) - n_T(\infty)] \exp[-(e_n + e_P)t] \qquad (2)$$

where n_T (o) and n_T (∞) are expressed, respectively, by

$$n_T(0) = N_T\left[1 + \frac{e_n + c_P \Delta p}{e_P + c_n \Delta n}\right]^{-1} \qquad (3a)$$

and

$$n_T(\infty) = N_T\left[1 + \frac{e_n}{e_P}\right]^{-1} \qquad (3b)$$

Here, Δn and Δp are, respectively, excess carriers generated by the photoexcitation, and c_n and c_p are, respectively, capture rates for electrons and holes. The emission rates, in general, are much lower then capture rates at high-level exitations. Under this condition and assumption $e_n >> e_p$ for electron traps, Eq.(2) can be rewritten as

$$\delta i(t) = K\ N_T\ e_n \exp(-e_n\ t) \qquad (4)$$

2. *Transport Measurements*

Hall measurements on semi-insulating semiconductors become difficult due to surface leakage problems. In addition, due to the high resistivity, the measurements have to be performed at $T > 300K$. Since mixed-carrier conduction is operative, the conductivity, Hall coefficient and Hall mobility are calculated theoretically for the entire temperature range of measurement by considering the different carrier-scattering mechanisms and using Matthiesen's rule. [8] Neutral impurity scattering needs to be included because of the proximity of deep compensating levels to the Fermi level in semi-insulating materials. The mobility due to scattering by neutral impurities, including the short-range attractive potential of the neutral centers, N_{NI}, is [9]

$$\mu_{NI} = \frac{1.17 \times 10^{22}(m^*/m_o)}{\varepsilon_r \varepsilon_o N_{NI}} (7.34 \times 10^{-3}\delta + 30.2/\delta) \qquad (5a)$$

where

$$\delta = \varepsilon_r \varepsilon_o \sqrt{T/(m^*/m_o)} \qquad (5b)$$

where ϵ_r is relative permittivity, m^* is effective mass, and T is absolute temperature. The Fermi energy, E_F, is determined from an accurate solution of the charge neutrality equation by Newton's iterative method. With reference to Fig. 1(a) the equations for a material with a single deep compensating acceptor level are developed below. Additional levels can be readily incroporated. The charge neutrality condition for shallow donor and acceptor levels and a deep acceptor level, in the mid-band gap region, can be written as

$$n=p+N_D^+-N_A^--N_{AA}^- \qquad (6)$$

where N_{AA} denotes the ionized densities of the deep acceptors. If full ionization is assumed for the shallow levels (N_D and N_A), then Eq.(6) may be written as

$$n=p+(N_D-N_A)-\frac{N_{AA}}{1+g_{AA}\exp[(E_{AA}-E_F)/kT]} \qquad (7)$$

where g_{AA} is the degeneracy factor of the deep acceptor level and k is Botzmann's constant. Eq. (7) can also be rewritten as

$$n^2+n\left[\frac{N_{AA}}{1+F_{AA}/n}-(N_D-N_A)\right]-n_i^2=0 \qquad (8)$$

where

$$F_{AA}=g_{AA}\,N_C\,\exp[(E_{AA}-E_G)/kT] \qquad (9)$$

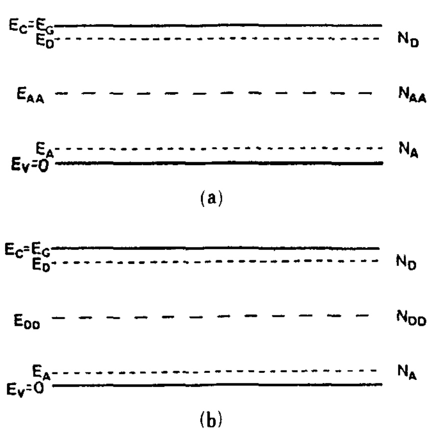


Fig.1. Energy level models used to analyze transport data in semi-insulating semiconductors with (a) a single deep compensating acceptor level, (b) a single deep compensating donor level.

and N_{AA} and N_C are the total concentration of deep-level acceptors and effective density of states in the conduction bands, respectively. Here, the temperature dependence of forbidden energy gap, E_G (T), is given by [10]

$$E_G(T)=1.519-\frac{5.4\times10^{-4}T^2}{T+204}\,[eV] \qquad (10)$$

The Fermi function can alternately be written as

$$f(E_{AA})=\frac{1}{1+g_{AA}\frac{N_C}{n}\exp[(E_{AA}-E_G)/kT]} \qquad (11)$$

The quantity $N_{AA}/(N_D\text{-}NA)$ is the degree of compensation, when its value is less than unity, $n = N_D\text{-}N_A$. When its value is greater than or equal to unity, n decreases drastically with increase in the value of the compensation ratio and its value approaches that of n_i. Therefore, for the deep acceptors to control the resistivity in the semi-insulating semiconductor, the following conditions must hold:

$N_D>N_A$ and $N_{AA}\geq N_D-N_A$

For such cases, the solution to Eq.(8) may be approximately written as

$$n\simeq F_{AA}\Big/\left(\frac{N_{AA}}{N_D-N_A}-1\right) \qquad (12)$$

This equation is true when n has a low value and is nearly equal to p. and mixed carrier condition leads to

$$\sigma(T)=\frac{q\mu_n N_V}{g_{AA}b}[CR-1]\left\{\exp\left(-\frac{E_{AA}}{kT}\right)\right.$$
$$\left.\frac{g_{AA}^2\,bN_C}{N_V(CR-1)^2}+\exp\left(-\frac{E_G-E_{AA}}{kT}\right)\right\} \qquad (13)$$

and

$$R_H(T)=r\,\frac{g_{AA}}{qN_V(CR-1)}$$
$$\frac{\exp\left(\frac{E_{AA}}{kT}\right)-g_{AA}^2\,b^2\,N_C\,\exp[(3E_{AA}-E_G)/kT]/N_V(CR-1)^2}{\{1+g_{AA}^2bN_C\exp[(2E_{AA}-E_G)/kT]/N_V(CR-1)^2\}^2} \qquad (14)$$

where CR= $N_{AA}/(N_D\text{-}N_A)$ and b= $\mu n/\mu p$ similarly, with reference to Fig.1(b), the charge neutrality condition in a material with a single deep donor level can be expressed.

III. Experiments

1. Device for PICT measurements

The semi-insulating (SI) GaAs samples used for this study were grown either by the Liquid Encapsulation Czochralski (LEC) technique or by the horizontal Bridgman technique and were normally oriented in the (100) direction. The resistivity in the samples is ~1E8 ohm-cm at room temperature. Device were made from samples of SI GaAs 5 x 5 mm^2 in area and having a thickness of 200-300 μm. The samples were degreased and etched for 5-10sec. in 5 H_2SO_4:1 H_2O_2:1 H_2O at room temperature. A semitransparent circular Au film (diameter = 1.5 mm, thickness=100-200 Å) was deposited on the polished top surface and a thicker Au layer (~1000 Å) was deposited on the entire face by evaporation under a vacuum of ~1E-6 Torr.

2. Photo-Induced Current Transient Measurements

The Photo-Induced Current Transient (PICT) technique, first reported by Hurtes et al.[5], has to be employed since it is not possible to perform conventional capacitance transient measurements on materials exibiting high resistivity. The schematic of the PICT measurements is shown in Fig.2. Intrinsic photoexcitation generates electron-hole pairs just underneath the circular Au film. The excess carriers are captured by electron or hole traps in the sample, if they exist. After removal of the photoexciation, detrapping due to the thermal re-emission given rise to a transient current between the two contacts. Typical values of the bias applied between the Au contacts varied from 8 to 10 V. Arrhenius plots for the emissions detected in SI GaAs:Cr and undoped GaAs are shown in Figs. 3 and 4, respectively. For experiments with intrinsic photoexcitation, the distinction between electron and hole emissions can be made by observing the direction of the transient

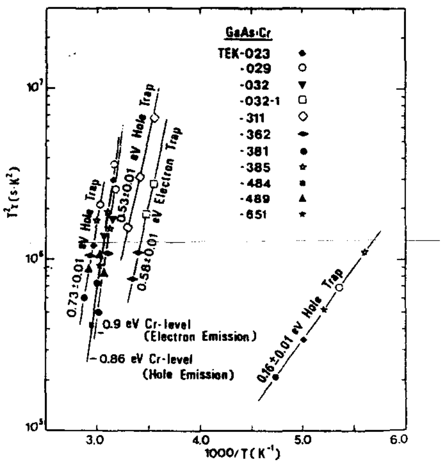


Fig.3. Arrhenius plots for electron and hole trap levels in SI GaAs: Cr. The symbols located arbitrarily represent the different samples and are not data points.

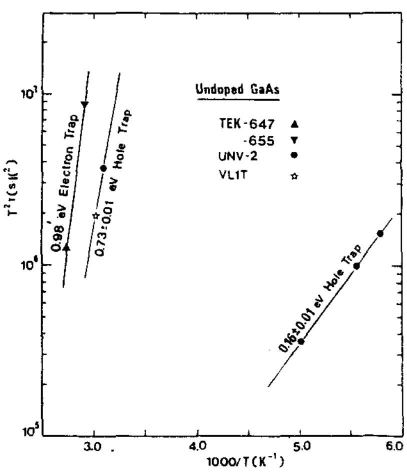


Fig.4. Arrhenius plots for electron and hole trap levels in SI undoped GaAs. The symbols located arbitrarily represent the different samples and are not data points.

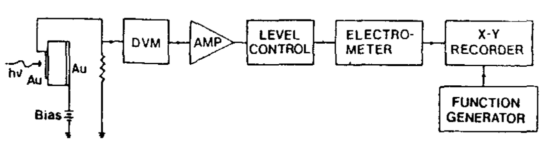


Fig.2. Schematic for Photo-Induced Current Transient measurements.

current variation. It should be noted that the activation energies, ΔE_T, in Tables 1 and 2 were obtained from the slopes of ln (T^2 τ) vs. 1/T plots and include the barrier energy ΔE_B. Similarly, the capture cross sections, σ_∞, were obtained from the emission rate. The true

Table 1. Characteristics of Deep levels in SI GaAs : Cr.

Sample	Electron Trap		Hole Trap	
	ΔE_T (eV)	σ_∞ (cm²)	ΔE_T (eV)	σ_∞ (cm²)
TEK023			0.86 0.73 0.16	1.2×10^{-13} 5.1×10^{-17} 3.9×10^{-22}
TEK029	0.90	2.2×10^{-12}	0.87 0.74 0.16	1.2×10^{-13} 5.0×10^{-17} 4.0×10^{-22}
TEK032	0.89	2.1×10^{-12}	0.86	1.1×10^{-13}
TEK0321	0.58	4.5×10^{-17}		
TEK311			0.53	3.2×10^{-19}
TEK362	0.90 0.58	2.3×10^{-12} 4.6×10^{-17}	0.72	5.2×10^{-7}
TEK381	0.91	2.1×10^{-12}	0.85 0.73 0.15	1.2×10^{-13} 5.1×10^{-17} 3.8×10^{-22}
TEK385	0.90	2.2×10^{-12}	0.86 0.73 0.16	1.2×10^{-13} 5.1×10^{-17} 3.9×10^{-22}
TEK484			0.87	1.1×10^{-13}
TEK489	0.90	2.2×10^{-12}	0.86 0.72	1.2×10^{-13} 5.0×10^{-17}
TEK651			0.86 0.17	1.3×10^{-13} 3.9×10^{-22}

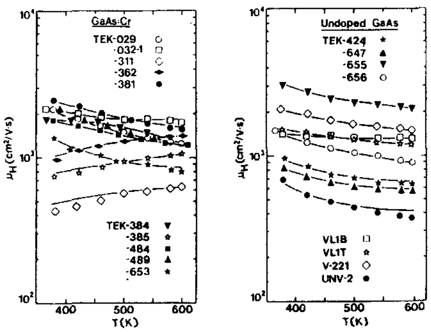
Table 2. Characteristics of Deep Levels in SI Undoped GaAs.

Sample	Electron Trap		Hole Trap	
	ΔE_T (eV)	σ_∞ (cm²)	ΔE_T (eV)	σ_∞ (cm²)
TEK657	0.98	1.6×10^{-13}		
TEK655	0.97	1.5×10^{-13}		
UNV2			0.73 0.16	5.1×10^{-17} 3.9×10^{-22}
VLIT			0.74	5.0×10^{-17}

capture cross section of the centers can be obtained from a measurement of the thermal capture rates.[11]

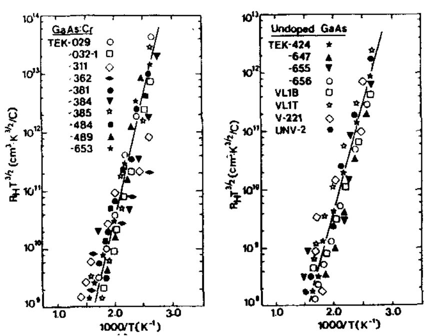
3. Transport Measurements

The variations of Hall electron mobility with temperaure in the range 380-600 K for semi-insulating Cr-doped and undoped GaAs are depicted in Fig.5(a) and (b), respectively. The variations of $R_H T^{3/2}$, and dark conductivity, σ, with inverse temperature and shown in Figs. 6 and 7(a) and (b) for SI GaAs: Cr and undoped GaAs, respectively. The variations are almost linear in the temperature range of interest. The measured transport parameters at 400 K in SI GaAs: Cr and undoped GaAs are listed in Tables 3 and 4, respectively.



(a) (b)

Fig.5. Variation of Hall mobility with temperature in (a) SI GaAs: Cr and (b) SI undoped GaAs.

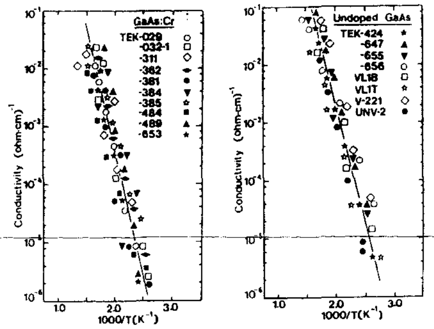


(a) (b)

Fig.6. Plots of $R_H T^{3/2}$ versus inverse temperature in (a) SI GaAs: Cr and (b) SI undoped GaAs.

IV. Experimental Result and Discussions

Theoretical fits to the vaiations of Hall mobility with temperature are indicated by the solid lines



(a)　　　　　(b)

Fig.7. Plots of dark conductivity, σ, versus inverse temperature in (a) SI GaAs: Cr and (b) SI undoped GaAs.

in Fig.5. In some SI GaAs: Cr samples the Hall mobility is seen to increase with temperature. A probable reason is that the impurity concentration is inhomgeneously distributed through the sample[12,13]. Piezoelectric scattering was found to have a negligible contribution to the total mobility. A Hall scattering factor of unity was assumed for simplicity. It was also found that $\mu_H = \mu_n$ for all samples in the temperature range of interest and the hole mobilities could be ignored. The parameters used for calculating the mobilities limited by polar optical phonon, deformation and piezoelectric scattering. The final values of the concentrations and the compensation ratios are listed in Table 5 for SI GaAs: Cr and Table 6 for SI undoped GaAs, respectively. Values for the deep acceptor and donor concentrations, N_{AA} and N_{DD}, and their energy depth measured from the conduction band edge, were estimated by fitting the experimental values of $R_H T^{\frac{3}{2}}$, and σ using the theoretical equations derived in Chapter II. The estimated values of (E_G-E_{AA}) and (E_G-E_{DD}) are listed in Tables 3 and 4 and of N_{AA} and N_{DD} in Tables 5 and 6.

Photocurrent spectra were performed to confirm some of the results obtained from PICT an high-temperature Hall measurements and to detect deep levels which may not have been revealed by the previous measurements. The photocurrent spectra were recorded in the spectral range 0.4 - 1.5 eV with a Jarrel Ash monochromator with an appropriate combination of filters. The device configuration was the same as that for the PICT measurements. The constant electric field across the samples varied in the range (1.0-3.5) x 10^2 V/cm. Typical photocurrent spectra in SI GaAs: Cr at 100 and 203K are shown in Fig.8 (a). Chromium in GaAs is usually located in a Ga site giving rise to a deeplying acceptor impurity Four charge-states of the Cr-related centers have been reported[14], giving rise to multiple activation energies between 0.56 to 0.9 eV. [15] The onset at 0.65 eV has been observed by several investigators and is probably related to oxygen. [15,16] The rise in photosensitivity at 0.81 eV is probably due to Cr. [15,17] The peak at ~ 1.0 eV has been attributed to the intratransition from the $^5T_2$ ground state to the ^5E excited state of

Table 3. Transport data in SI GaAs : Cr obtained from hall measurements. Also listed are the values of the fermi Energy at 400K and energy position of the deep acceptor levels derived from analysis of hall-enffect data.

Sample	$(qR_H)^{-1}$ at 400K (cm^{-3})	μ_H at 400K (cm^2/V. s)	Slope of $\ln(R_H T^{3/2})^{-1}$ (eV)	(E_G-E_{AA}) From Analysis (eV)	(E_G-E_F) at 400K From Analysis (eV)
TEK 029	5.8×10^{9}	2020	0.82	0.81	0.64
TEK 0321	1.7×10^{10}	2100	0.84	0.83	0.60
TEK 311	2.0×10^{11}	275	0.65	0.83	0.52
TEK 362	4.0×10^{10}	790	0.66	0.83	0.57
TEK 381	7.2×10^{9}	2450	0.80	0.81	0.63
TEK 384	1.0×10^{10}	1880	0.80	0.82	0.62
TEK 385	6.0×10^{11}	560	0.85	0.84	0.48
TEK 484	1.7×10^{10}	1770	0.81	0.82	0.60
TEK 489	2.8×10^{10}	1950	0.86	0.83	0.58
TEK 653	1.1×10^{10}	1250	0.87	0.83	0.62

Table 4. Transport data in SI undoped GaAs obtained from hall measurements. also listed are the values of fermi energy at 400K and energy position of the deep donor levels derived from analysis of hall-effect data.

Sample	$(qR_H)^{-1}$ at 400K (cm^{-3})	μ_H at 400K (cm^2/V. s)	Slope of $\ln(R_H T^{3/2})^{-1}$ (eV)	$(E_G - E_{DD})$ From Analysis (eV)	$(E_G - E_F)$ at 400K From Analysis (eV)
TEK424	1.25×10^{11}	890	0.75	0.74	0.53
TEK647	7.8×10^{11}	780	0.67	0.72	0.47
TEK655	2.3×10^{11}	2950	0.71	0.72	0.51
TEK656	4.2×10^{11}	1350	0.68	0.73	0.49
UNV2	3.2×10^{10}	600	0.77	0.75	0.58
VL1B	1.9×10^{11}	1425	0.65	0.71	0.52
VL1T	7.5×10^{10}	1475	0.74	0.74	0.55
V221	1.85×10^{11}	2075	0.71	0.72	0.52

Table 5. Shallow and deep acceptor level concentrations and compensation ratios in SI GaAs : Cr determined from analysis of hall-effect data.

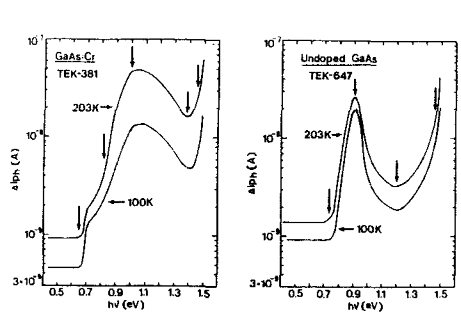
Sample	N_{AA} (cm^{-3})	N_D (cm^{-3})	N_A (cm^{-3})	$\frac{N_{AA}}{N_D - N_A}$
TEK029	4.2×10^{16}	3.0×10^{16}	2.1×10^{16}	4.6
TEK0321	2.3×10^{16}	2.8×10^{16}	2.0×10^{16}	2.8
TEK311	1.19×10^{17}	2.0×10^{17}	1.0×10^{17}	1.19
TEK362	1.9×10^{16}	7.5×10^{16}	6.5×10^{16}	1.9
TEK381	2.5×10^{16}	2.9×10^{16}	2.1×10^{16}	3.1
TEK384	3.5×10^{16}	3.3×10^{16}	2.3×10^{16}	3.5
TEK385	1.08×10^{16}	9.4×10^{16}	8.4×10^{16}	1.08
TEK484	2.5×10^{16}	3.6×10^{16}	2.6×10^{16}	2.5
TEK489	1.8×10^{16}	3.1×10^{16}	2.2×10^{16}	2.0
TEK653	3.0×10^{16}	3.5×10^{16}	2.5×10^{16}	3.0

Table 6. Shallow and deep donor level concentrations and compensation ratios in SI Undoped GaAs determined from analysis of hall-effect data.

Sample	N_{DD} (cm^{-3})	N_D) (cm^{-3})	N_A (cm^{-3})	$\frac{N_{DD}}{N_A - N_D}$
TEK424	2.1×10^{17}	9.0×10^{16}	9.8×10^{16}	26.25
TEK647	1.4×10^{18}	1.0×10^{17}	1.1×10^{17}	140.0
TEK655	4.3×10^{16}	9.0×10^{15}	1.0×10^{16}	43.0
TEK656	3.2×10^{17}	2.3×10^{16}	2.7×10^{16}	80.0
UNV2	2.2×10^{17}	1.8×10^{17}	2.1×10^{17}	7.3
VL1B	7.2×10^{16}	2.2×10^{16}	2.4×10^{16}	36.0
VL1T	3.0×10^{16}	2.1×10^{16}	2.3×10^{16}	15.0
V221	3.5×10^{16}	1.7×10^{16}	1.8×10^{16}	35.0

Cr^{2+}. [18] The transition at 1.39 eV was observed for the first time in this study. It may be due to electron transition from an ubiquitous impurity or defect level.

With reference to Fig.8 (b), which depicts the photocurrent spectra for SI undoped GaAs, the onset at 0.73 eV has been observed by several investigators and is attributed to oxygen. [19,20] The transition at 1.2 eV has been observed by Williams [21] and Farbe [22], but its origin is yet unknown. The hole trap with ΔE_T=0.86 ± 0.01 eV, which is detected in almost all the SI GaAs: Cr samples, is attributed to Cr. [23] The 0.90 ± 0.01 eV electron trap level detected in the same samples is attributed to electron emission from the same centers. [11,24] The 0.58 ± 0.01 and 0.53 ± 0.01 eV electron and hole trap levels, respectively, are ascribed to unknown impurities. The electron trap may be identical to the 0.60 eV electron trap reported by Fairman and Oliver [25] in SI GaAs or center EL3 (0.575 eV) reported by Martin et al. [26] in VPE GaAs. The hole trap has thermal activation energy and



(a)　　(b)

Fig.8. Photocurrent spectra obtained at T= 203 and 100K for (a) SI GaAs: Cr and (b) SI undoped GaAs.

capture cross section very similar to trap HS_1 (0.58 eV) reported by Mitonneau et al. [27] in LPE GaAs. The 0.73 ± 0.01 eV hole trap level also detected in SI undoped GaAs, has a thermal activation energy very similar to trap B (0.71 eV) detected by Lang and Logan [11] in LPE GaAs and related to a native defect. However, the thermal hole capture cross sections are at least 2 or 3 orders higher than for the 0.73 eV centers detected in this study. The 0.16 eV hole trap level, detected for the first time in this study, can probably be ascribed to native defects since it was detected in both SI GaAs: Cr and undoped GaAs. Fewer deep levels were detected in SI undoped GaAs. The 0.98 ± 0.01 eV electron trap level, detected for the first time in this study, can be ascribed to unknown impurities and further studies are necessary to elucidate its orgin.

The presence of Cr was confirmed by high-temperature Hall and photocurrent measurements. Similarly the presence of the deep donor level at Ec-0.73 eV detected by high-temperature Hall measurement on SI undoped GaAs was confirmed by the photocurrent measurments. This level could not be detected by the PICT measurements due to strong optical quenching, possibly by the deep level at Ev + 0.9 eV. The consistency in the values of the ionization energy obtained from the different measurements indicates minimal lattice coupling associated with these centers.

V. Conclusions

The high resistivity is brought about by compensating single deep acceptor-like levels in Cr-doped semi-insulating materials, and by single deep donor-like levels, possibly related to "O", in undoped semi-insulating GaAs. The thermal ionization properties of the Cr-related level have been determined from Photo-Induced Current Transient measurement. 0.73 ± 0.01 and 0.16 ± 0.01 eV hole trap levels detected in SI GaAs by the same measurement technique are ascribed to unknown impurities or defects. An electron trap level with an activation energy of 0.98 ± 0.01 eV in undoped SI GaAs was detected for the first time in this study and is related to unknown impurities. Hall effect data obtained for the Semi-insulating materials at high temperature have been analyzed in detail taking into account the various relevant scattering mechanisms. Neutral impurity scattering is found to play an important role in limiting carrier mobilities at high temperatures. The various transport parameters and the Fermi energies have been estimated from computer analyses on the basis of charge neutrality conditions. Comparison of PICT, Hall effect and photocurrent data has enabled the accurate determination of the energy position of the Cr-levels in SI materials. The Cr-level in SI GaAs :Cr is located at ~0.82 eV below the conduction band edge at room temperature. The consistency in the values of the ionization energy for the compensating centers obtained from the different measurements suggests that they have minimal lattice coupling. The deep donor level with an activation energy of 0.73 eV observed in SI undoped GaAs by Hall effect and photocurrent measurements was not detected by PICT measurements. This is probably due to optical quencing effects. In general, the SI undoped GaAs has fewer deep levels than SI GaAs:Cr.

Some suggestions may be made for future work intended to extend the scope of the present study. A more systematic study is necessary to determine the physico-chemical origin of various traps detected in this study, and to develop processes to eliminate them.

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