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Variable Range Hopping Conduction in Low-Temperature Molecular Beam Epitaxy GaAs

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Electric transport properties measured by Van der Pauw resistivity experiments of Low-Temperature Molecular Beam Epitaxy (LT-MBE) GaAs samples are used to identify a method to improve the resistivity of GaAs material. We present results on five samples grown at 265, 310, 315, 325, and 345 ^{o}C. The electric measurements were carried out at temperatures ranging from 130 to 300 K. In this temperature range the dominant transport process is identified as variable range hopping. The hopping parameter plotted against the growth temperature is shown to present a maximum. The mechanisms responsible for this behavior are discussed in relation to the compensation ratio.

Keywords: GaAs; Variable range hopping; Resistivity measurements

I. INTRODUCTION

The search of GaAs layers grown by MBE with good quality semi-insulating (SI) properties has been pursued for at least two decades [1] and it can be improved by the control of intrinsic defect density through the growth temperature.

The SI characteristic is related to the presence of intrinsic deep level defects [2]. Although deep levels leads to recombination, in high enough density it also transport carriers by hopping. This is an undesirable characteristic. In the present work we varied the growth temperature in an attempt to maximize the resistivity.

Albeit its technological implications, from the academic point of view, the study of hopping conduction of deep level defects on GaAs offers a fruitful platform for the study of hopping conduction at temperatures as high as the room temperature [3,4]. Previous reports on the literature have identified hopping conduction among arsenic antisite defects (As_{Ga}) in GaAs [3,4]. We present here our results for resistivity measurements in five LT-MBE GaAs samples. The contributions of the present work concern only to the Variable Range Hopping (VRH).

Temperature dependent Van der Pauw resistivity measurements for the five samples show VRH signature associated with the law $\rho = \rho_0 \exp(T_0/T)^{1/4}$ over a wide temperature range. The parameter $T_0^{1/4}$ is an indirect measurement of the density of centers participating in hopping conduction and is a signature of the VRH. It is observed that for increasing growth temperature (T_G) the hopping parameter presents a maximum at 315 ^{o}C. Such feature is associated with a low compensation ratio. Another important issue concerns the trapping characteristics of deep level defects in the temperature range considered in this work. This makes negligible any contribution of shallow extrinsic impurities and of free carriers as indicated by pure VRH.

II. EXPERIMENTAL DETAILS AND RESULTS

In the present work we report on VRH in LT-MBE GaAs samples grown at 265, 310, 315, 325, and 345 ^{o}C. The LT-GaAs layers were grown on (100) semi-insulating LEC GaAs substrates, in a RIBER 2300 MBE system. After the standard desorption procedures a buffer layer 0.21 μm thick was grown at 610 ^{o}C under an As overpressure of 3.2×10^{-5}Torr and 0.81 monolayer/s. After that the substrate temperature was ramped down to the final desired temperature at 10 ^{o}C/min while growing. After reaching the set temperature GaAs epilayers were grown having around 2.4 μm thick.

Microprobe analyses were carried out in order to determine the excess arsenic of the samples by comparing them with a standard GaAs wafer. The measurements were done in a JEOL JXA-8900RL in the wavelength dispersive mode considering 10 different regions per sample, 1μm diameter spots, an acceleration voltage of 25 kV, and a counting time of 10 s. The excess arsenic as a function of the growth temperature are listed in Table I.

TABLE I: Hopping parameters

Sample # (T_G^oC)	Excess As(%)	$T_0^{1/4}$(K$^{1/4}$)	N_h(cm^{-3})
1 (265)	1.95	99.0±0.5	$(4.7\pm0.1)\times10^{19}$
2 (310)	1.80	190±1	$(9.3\pm0.1)\times10^{18}$
3 (315)	1.77	370±2	$(1.7\pm0.1)\times10^{16}$
4 (325)	1.84	260±1	$(1.4\pm0.1)\times10^{18}$
5 (345)	1.71	232±1	$(2.8\pm0.1)\times10^{18}$

For the resistivity van der Pauw measurements the samples were cut into 5x5 mm^2 squares and the contacts were made of indium drops. The samples were then baked at 250 ^{o}C for 10 min under flowing inert gas. The measurements were carried out in the "ohmic" regime (i.e. under applied bias which respect the linearity of the ohm's law). The ohmic range of

the applied bias was previously identified from I(V) conductivity measurements, which were carried out from negative to positive bias.

For each growth temperature, we have prepared at least seven samples from different parts of the wafer and the results did not vary significantly in a same wafer. For the resistivity measurements, we have used a Keithley electrometer model 6517 and a current/voltage source Keithley model 237. Both instruments were used with triaxial cables in guarded-mode measurements. The electric transport measurements were carried out at temperatures ranging from 130 to 300 K.

Resistivity measurements in a logarithmic scale as a function of $T^{-1/4}$ are shown in Fig. 1. Standard VRH (variable range hopping) corresponds to the range of linear dependence of measurements in this diagram [5]. The values of $T_0^{1/4}$ obtained by fitting this linear region are listed in Table I.

III. DISCUSSION

According to Mansfield [6] the active center density carrying Variable Range Hopping (VRH) – denoted N_h – can be obtained from T_0 (in K) combining the following expressions:

$$T_0 = \frac{49}{kN_0a^3},\tag{1}$$

and

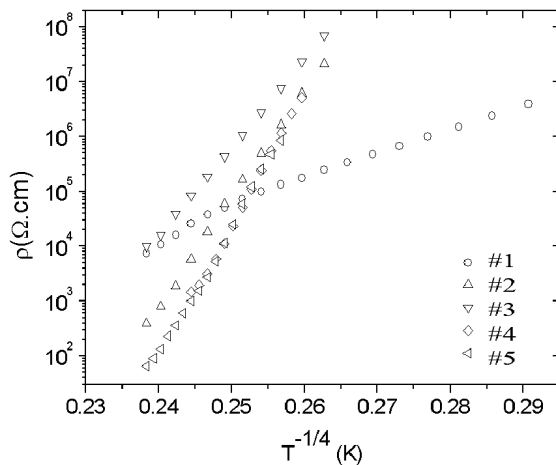$$N_0 = \frac{\kappa N_h^{2/3}}{e^2}\tag{2}$$

FIG. 1: VRH characteristic resistivity plot versus $T^{-1/4}$.

In Eq. (1) factor 49 is the percolation parameter, k is the Boltzmann's constant and a is the wave function localization radius of the hopping active center. The value of a, which estimated the localization radius of the defect, was estimated to be 4 Å from X-ray diffraction experiments by Shimoghishi et.

al. [7]. Finally, Eq. (2) relates N_0 to N_h, where the dielectric constant κ is assumed to be $12.9\in_0$ for GaAs [3] (where $\in_0$ is the vacuum dielectric constant) and e is the electron charge. N_0 is directly related to the density of states associated with the As_{Ga} [6]. It should be noted that $N_h < N_D$, i.e., N_h is always smaller than N_D, which is the As_{Ga} donor density or any other defect responsible for the VRH effect. Since N_h values were obtained from $T_0^{1/4}$ which is obtained by linear fittings of Fig. 1 its value holds for the temperature range considered in the fittings.

The hopping conduction involves only the energy levels within a narrow range near the Fermi level, and this range shrinks as the temperature is reduced [8]. By decreasing the temperature, the active defect density for hopping conduction also decreases. The shrinking of the narrow energy range is the key mechanism behind the $\exp(T_0/T)^{1/4}$ law for VRH.

In Table I, besides the excess arsenic and the $T_0^{1/4}$ values, we listed the N_h values calculated using Eq.(1) and Eq.(2). The ionization energy of the defect center was 0.65 eV [4].

In this work we improved substrate characteristics by adjusting the growth temperature and reducing N_h. Since microprobe measurements indicates an almost constant excess arsenic which implies in low As_{Ga} density changes. The reduction in N_h can be associated with the compensation factor [6].

Based on the results presented in Table 1, the main outcomes can be summarized as follows. The order of magnitude of N_h, derived from resistivity measurements and Eq.(1) and Eq.(2), decreases from 10^{19}cm^{-3} for sample #1 to 10^{18}cm^{-3} for sample #2 and further to a minimum at 10^{16}cm^{-3} for sample #3. The sample #3 presents the lowest N_h value and for further increasing T_G, N_h increases back to 10^{18}cm^{-3}. A minimum in N_h must be related to a low compensation levels and not to a real decrease in the As_{Ga} density.

The microprobe analysis indicates excess arsenic between 1.71% and 1.95%. In first approximation it can be considered constant, when compared with the huge significant change in the hopping active defects density N_h (namely, three orders of magnitude). The As_{Ga} defect density (N_D) of sample #3 is expected to be around 10^{19}cm^{-3}, [9] only one order of magnitude lower than sample #2 and the same order of the other samples. Another mechanism must be therefore considered in order to understand the reduction of the density of active centers supporting VRH. The As_{Ga}^+ density depends directly on the acceptor density N_A. In LT-MBE GaAs the gallium vacancies V_{Ga} play the major role as acceptors [10]. This defect is known as a deep triple acceptor [7]. Regarding the V_{Ga} concentrations, Gebauer et al. [10] found densities of 10^{18} cm^{-3} and 10^{17}cm^{-3} for T_G of 200 ^{o}C and 300 ^{o}C, respectively.

Our work indicates that it is possible to obtain good quality semi-insulating GaAs epilayers required for applications in devices with low sidegating effects. We have shown that is possible to maximize the resistivity value by controlling the hopping parameter $T_0^{1/4}$ through the growth temperature. The presence of acceptors is another important experimental factor to be considered. Thus it is important to produce samples rich in AsGa but with negligible acceptor concentrations. Our LT-

MBE samples grown at 315 ^{o}C are highly resistive, presenting a higher hopping parameter $T_0^{1/4}$.

IV. SUMMARY

We carried out high-precision van der Pauw resistivity measurements on five GaAs samples grown by low temperature molecular beam epitaxy (LT-MBE) at 265, 310, 315, 325, and 345 ^{o}C. Our results show that the samples grown at 265 ^{o}C present resistivity and hopping parameters similar to previous ones [3]. The other samples present higher hopping parameter with an extremum for the sample grown at 315 ^{o}C. This result could be understood in the framework of the Variable Range Hopping mechanism, and indicates that very high insulating materials can be obtained by LT-MBE, when the proper growth temperature window is chosen.

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