Low-temperature conductivity of epitaxial ZnSe in the impurity band regime

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Low-temperature conductivity of several samples of ZnSe grown by molecular-beam epitaxy has been measured. The data indicate that for samples with carrier concentration below or near N_c, metal insulator transition, the conductivity obeys $\sigma=\sigma_0 \exp[-(T_0/T)^s]$ at low temperatures with $s=1/2$. This behavior is a characteristic of variable-range hopping conduction in the presence of a Coulomb gap. © *1994 American Institute of Physics.*

Impurity conduction is a phenomenon normally expected to occur in compensated semiconducting materials with doping concentration below metal–nonmetal transition at low temperatures. The phonon-assisted tunneling, hopping, is a dominant form of conduction in this process. Mott[1] was first to point out that the most frequent hopping would not be a nearest neighbor hopping. As a result, the average hopping or activation energy will be temperature dependent. This form of conduction is called variable-range hopping (VRH) and the conductivity in this regime obeys the relation:

$$\sigma=\sigma_0 \exp[-(T_0/T)^S]. \tag{1}$$

When $s=1/4$, Eq. (1) is known as Mott's Law. Efros and Shklovski[2] have shown that the Coulomb interactions between localized electron states produce a so-called Coulomb gap in the density of states. In this case the conductivity obeys Eq. (1) with $s=1/2$. In the presence of a Coulomb gap

$$k_B T_0 \approx 2.8 e^2/\epsilon\alpha, \tag{2}$$

in which ϵ is the dielectric constant and a is the localization length. Since VRH occurs in samples with an impurity concentration very close to the critical concentration, the analysis of the experimental data, using Eq. (2), usually gives very large values for localization length and dielectric constant.[3] In addition, if T_0 is large in comparison to the temperature in which hopping conduction takes place, then the exponential is the dominant factor and the slight temperature dependence of σ_0 in Eq. (1) is insignificant.

Variable-range hopping has been observed in large numbers of crystalline and amorphous semiconductors.[4,5] So far no such study has been reported on epitaxial ZnSe systems except the work reported by Marshall *et al.*[6] In their study it was found that at low temperatures (10–20 K) the resistivity in the impurity band regime obeys Mott's Law with $s=1/4$. However, their measurements span only over a small range of temperatures. In this work we span our measurements over a wider temperature range, and we show that indeed in the impurity band regime the conductivity is governed by variable-range hopping with $s=1/2$ rather than $s=1/4$.

All samples being used in this study were doped with gallium and were grown on semi-insulating GaAs by molecular beam epitaxy. The growth conditions have been described elsewhere.[7] The carrier concentrations deducted from Hall measurements as well as the room-temperature mobilities are given in Table I. Using a transport model proposed for ZnSe by Ruda[8] the compensation ratios for these samples were estimated to be between 80% and 90%. The electron concentrations of these samples are smaller than the critical electron concentration, $N_C \approx 3.7\times10^{17}$ cm^{-3}, reported for ZnSe.[6] All measurements were performed on the samples with van der Pauw configuration. Two calibrated thermometers, one adjacent to the sample and the other mounted inside a copper block for controlling the temperature, were used to measure the temperatures very accurately.

It is well known that the temperature dependence of resistivity and the Hall coefficient provide useful information about the conduction mechanism in semiconducting materials. Figure 1 shows semilog plot of the resistivity and Hall coefficient for three representative samples. As is clear from this figure, the Hall coefficient possesses a clear maximum and the resistivity data show two activation energies. This type of behavior has been observed in many crystalline semiconductors and is characteristic of the change in conduction mechanism from thermally activated to impurity band conduction.[4,5] It is also similar to results reported by Marshall *et al.*[6] A rough estimate of the slope in the low-temperature portion of the resistivity data provides an activation energy about 1–3 meV which is much smaller than phonon energy in this material and is an indication of the phonon-assisted hopping conduction.

In order to determine an accurate value for the exponent s in Eq. (1), it is essential to measure the temperature of the sample very accurately over a wide range of temperatures. To fulfill such consideration the conductivity of each sample was remeasured in a different cryostat that allows us to extend the temperature range down to 2.0 K and keep the sample in direct contact with the cryogen.

In Fig. 2 the conductivity of one representative sample is plotted as a function of temperature, T^{-S}, for $s=1/2$ and $s=1/4$. It is clear from this figure that $s=1/2$ will describe data over a wider range of temperatures in the impurity band regime. If we disregard data points below 10 K, the $x=1/4$

TABLE I. σ_0, T_0, and s are the results of fitting Eq. (1) top the experimental data. The room-temperature electron concentrations, mobility, and the thickness of each sample are also given.

Sample	Thickness (μm)	n_{300} (cm^{-3}) ($\times10^{17}$)	μ_{300} (cm^2/V s)	σ_0 (Ω^{-1} cm^{-1})	T_0 (K)	s
1	2.1	1.3	275	0.13	150	0.52
2	2.6	1.8	300	0.37	119	0.50
3	2.5	1.5	395	1.66	383	0.40

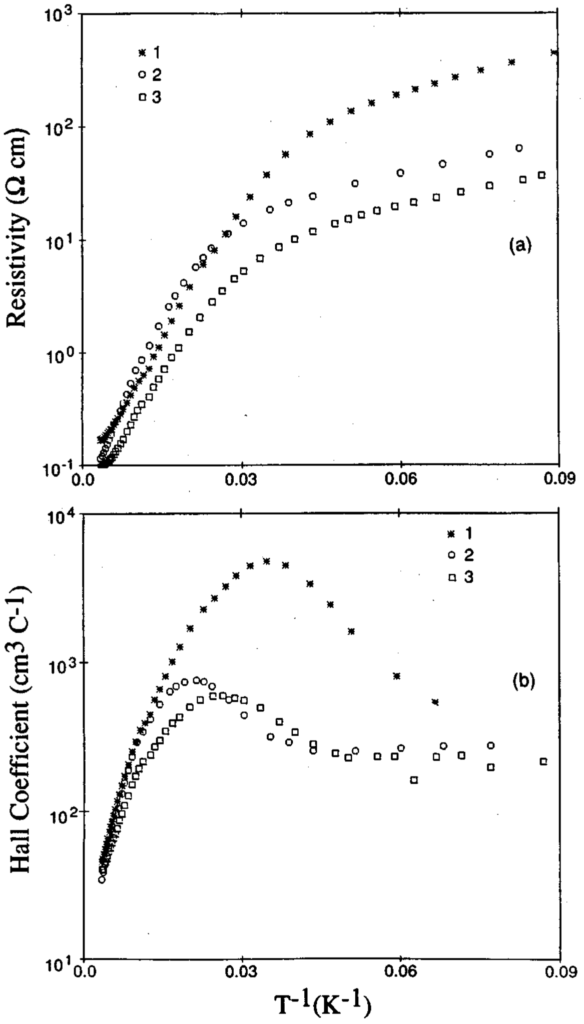

FIG. 1. Temperature dependence of the resistivity (a) and the Hall coefficients (b) for the three representative samples. The peak in the Hall coefficient and the smaller slope at low-temperature part of the resistivity data are characteristics of the impurity band conduction.

will also be a reasonable fit to the data and it agrees with the results reported in Ref. 6. Therefore, extending the temperature range below 10 K will allow us to identify clearly an accurate value for the exponent s in the Eq. (1). Figure 3 shows a plot of conductivity of three representative samples as a function of temperature, T^{-s}, with $s=1/2$. Again, this clearly indicates that in the impurity band regime the conductivity exponent is 1/2 rather than 1/4 for ZnSe epitaxial layers. It should be pointed out that similar temperature dependence, with $s=1/2$, for the conductivity of ZnSe layers was observed by Walsh *et al.*[9] at low temperatures. Their data were interpreted in terms of electron accumulation on the ZnSe side of the interface. However, such interpretation does not agree with the current understanding of ZnSe/GaAs interface.

In order to determine values of s and T_0 in Eq. (1) more accurately, the conductivity data were analyzed in a similar way as described in Ref. 10. The results of the fitting are given in the Table I. It is clear from the table that the values obtained for the exponent s are closer to 1/2 than 1/4.

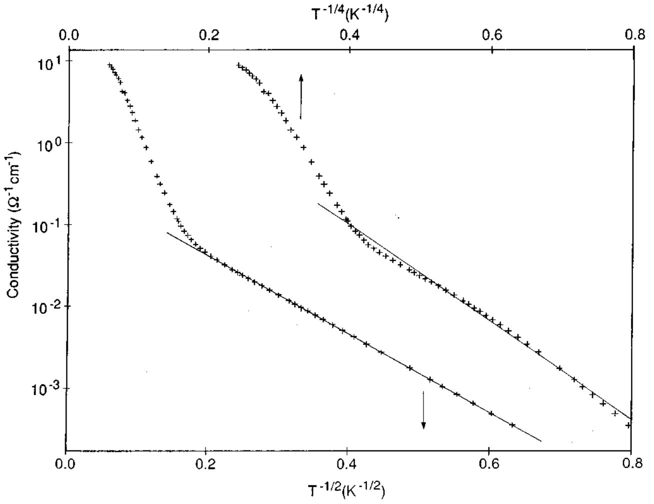

FIG. 2. Plot of the conductivity data vs $T^{-1/2}$ and $T^{-1/4}$. In the impurity band regime $T^{-1/2}$ provides an excellent fit to the experimental data.

Samples 1 and 2 are more compensated and provide a better fit with $s=1/2$. A large value of T_0 for sample 3 is a result of a smaller exponent, $s=0.4$, for this sample. If one fit the data for this sample with $s=0.5$, the value of T_0 for sample 3 would be almost the same as sample 2. This conclusion can be obtained from Fig. 3. The slope of each line in this figure gives $(T_0)^{1/2}$ for each sample. It is clear from this figure that samples 2 and 3 have almost identical slopes. So one cannot conclude that there is a large variation of T_0 with compensation. Using values of T_0 from Table I and Eq. (2), one can estimate values of ϵa. These estimates are an order of magnitude higher than values of ϵa calculated for ZnSe (ϵ=static dielectric constant≈9.2 and $a \approx 18$ Å). This discrepancy can be removed if one includes enhancement factors in the dielectric constant and the localization length of ZnSe in the VRH regime.[3] A much larger discrepancy has been reported for n-type CdSe.[11]

The magnetoresistances of these samples were also mea-

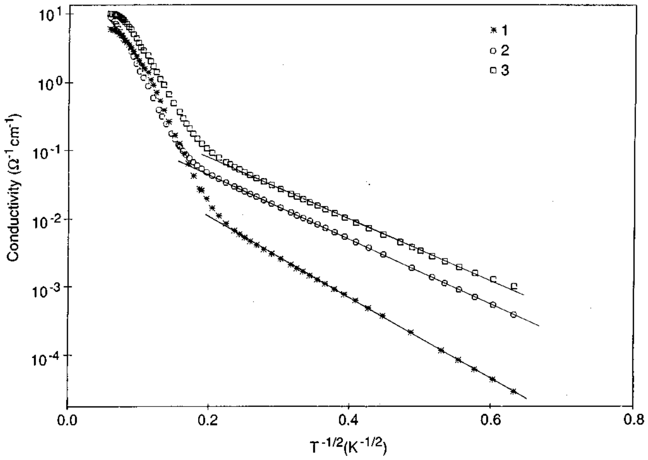

FIG. 3. Plot of the conductivity data vs $T^{-1/2}$ for the three representative samples.

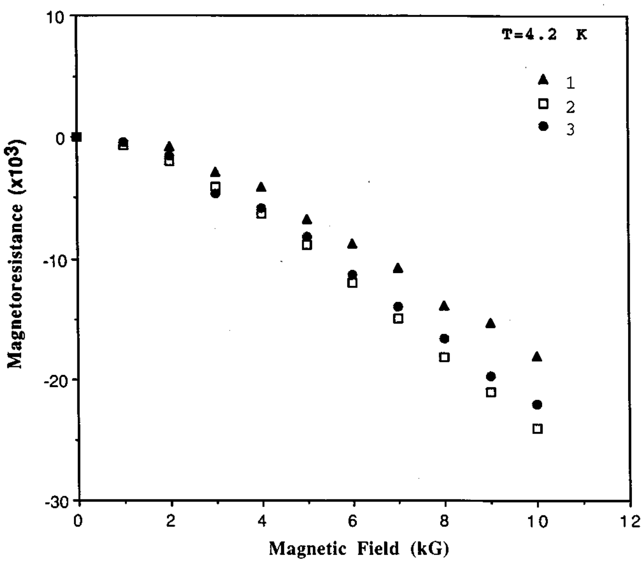

FIG. 4. Magnetoresistances of the three representative samples at $T=4.2$ K.

sured. All samples show quadratic negative magnetoresistance at low magnetic fields below 10 K. Figure 4 shows magnetoresistances of these samples at $T=4.2$ K. This behavior is a manifestation of quantum interference effect in the hopping conduction. The detailed analysis of these results will be discussed elsewhere.

In summary, we have shown that in the impurity band regime the conduction is by variable-range hopping and obeys Eq. (1) with the exponent $s=1/2$. This can be an indication that the long-range Coulomb interactions between the localized electron states produces a Coulomb gap in density of states near the Fermi energy for this material.

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