CHAPTER VI

DESIGN OPTIMIZATION FOR LOW RESISTANCE OHMIC CONTACT TO 
n-GaAs

INTRODUCTION

A noticeable progress has been made in recent years in contact technology. Nevertheless the research endeavours are being continued to reduce the resistance of a metal-semiconductor contact. The results in Fig. 4.3 to 4.6 in the chapter IV demonstrate that the contact resistance obtained in practice, for most of the semiconductors, are not close to the theoretical limitation, inspite of the application of advanced beam processing techniques for contact fabrication.

The purpose of the present study, is therefore, to optimize the parameters of an ohmic structure to obtain low resistance contacts. The design aspects of these parameters are discussed in the next section. Section 6.3 describes various mechanisms through which carriers are likely to lose their energy during transport across the interfacial n⁺ region of an ohmic junction. The subsequent section 6.4 considers physics of the relevant interactions to obtain optimum thickness of the intermediate n⁺ layer. Discussions are summarised in 6.5 followed by the concluding section 6.6 which briefly provides the guide lines, assesses the requirements and possible means to obtain low resistance ohmic contacts.
6.2 PARAMETERS OF A METAL-SEMICONDUCTOR OHMIC STRUCTURE

A metal - n+ - n structure is ohmic for n+ - region larger than metal - semiconductor (M-S) barrier width (1). A thick highly doped n+ - intermediate layer is therefore usually employed for making ohmic contacts to n - type semiconductors (2-4). The design parameters of an ohmic structure are (i) metal - n+ barrier height $\phi_1$ (ii) high - low junction barrier height $\phi_2$ (iii) carrier concentration $N_D$ in the n+ - region and (iv) n+ - layer thickness. These are depicted in Fig. 1.5 of the chapter.

The experimental results in Fig.1.2 (Chapter I ) show the independence of the M-S barrier height $\phi_1$ on the choice of a metal while eqn. (4.3) of the Chapter IV gives

$$\phi_2 = k T \ln \left( \frac{N_C}{N_B} \right) \quad (6.1)$$

Since substrate doping $N_B$ is determined by the device specifications and $N_C$, the effective density of states in conduction band is constant for a semiconductor, the high-low barrier height $\phi_2$ turns out to be a constant quantity for a given metal-semiconductor system.

We know that in a M-S junction, depletion region width is inversely proportional to the square root of carrier concentration in the semiconductor (5). Consequently, a high doping in the substrate results in a thin depletion region width at the interface, which has two important implications. Firstly, it enhances the tunneling through the barrier to yield a low resistance (6) and secondly it necessitates only a thin n+ - region for ohmicity of the junction.
However, a comprehensive review of contact technology in the section 1.3 and the gallium vacancy model in the chapter III evince that for alloyed contacts the doping is limited by interfacial interactions whereas it relies on the dopant solubility in case of epitaxial or implanted contacts (2-4). Therefore, it is not feasible to dope the interfacial layer very heavily in an attempt to minimise the contact resistance. In practical contacts, however, it is not essential to dope the $n^+$ region beyond a certain limit, since according to our ohmic model proposed in the chapter IV, the high-low barrier impedance predominates the contact resistance for $N_B < N_C$ (Figs. 4.3 to 4.6).

On the basis of the above discussions it can be conclusively established that for ohmicity of a M-S junction, the thickness and doping of the interfacial layer should be such that the Schottky barrier associated depletion region lies within it. However, if it is too wide, the hot electrons travelling across the M-S junction lose their energy during transit and may not be able to surmount the high-low barrier (7,8) of the ohmic structure to contribute to the current.

In case of alloyed contacts, the thickness of $n^+$ layer generated due to alloying is less than the electron mean free path (8,9) and all those electrons which possess energy higher compared to the high-low barrier height, constitute the current (9). Thus the carrier transport is ballistic i.e. collisionless. But in case of low resistance contacts formed by molecular beam epitaxy or implantation (2-4), the thickness of the $n^+$ region is generally larger than the carrier mean free path (10,11). Therefore, the hot electrons during
traverse through the undepleted part of the $n^+$ region encounter collisions and thereby lose their energy before arriving in the $n$-substrate. For an excessive loss of the energy, the density of current contributing carriers diminishes resulting in a high junction impedance. Therefore, to design a low resistance ohmic contact, carrier energy loss mechanisms are required to be considered (12-15) to determine the optimum thickness of the $n^+$ region.

6.3 CARRIER ENERGY LOSS MECHANISMS

Recent works conclude (16,17) that the effective barrier height $\phi$ of a metal-$n^+$-$n$ GaAs ohmic system is 0.4 eV. A tunneling electron, emitted with an energy $E_t$, at the M-S depletion edge may lose energy during transit through the neutral undepleted part of the $n^+$ region via a number of interactions such as:

(i) ionization collisions
(ii) intervalley scattering
(iii) electron-electron (e-e) collisions
(iv) scattering with impurities & defects
(v) electron-plasma interaction and
(vi) electron-phonon (e-p) scattering.

For not too energetic carriers as in the present case, the impact ionization collisions and intervalley scattering are unimportant (11,18). In electron-electron collisions there are no net energy losses, hence, they can be neglected. The carrier scattering with impurities and defects is not considered, as these are assumed to be elastic.
The electron plasma interaction is also omitted since for this process the carrier mean free path (500 Å) (10) is larger than the n⁺ - region thickness generally employed in an ohmic structure. Therefore, the interaction of hot electrons with phonons is a dominating process of energy relaxation and considered to estimate the n⁺ - region width in the following section. These presumptions concur with the recent studies concerning transport in the base region of a transistor and ballistic phenomenon in semiconductor devices (10-15, 18-23).

6.4 OPTIMUM THICKNESS OF n⁺ - REGION

The carrier interaction with phonon has two components (5, 19, 21, 24) : polar optical and acoustical. Initially, hot electrons lose energy to optical modes, as the loss rate of this interaction dominates for carrier energy larger than 3 Eₚ , then the loss to acoustical phonons become prominent (24). The average energy loss per collision for optical phonon scattering is given by (25)

\[ <E_p> = E_p \tanh \left( \frac{E_p}{2 KT} \right) \]  \hspace{1cm} \text{(6.2)}

where \( E_p \) is the optical phonon energy, \( K \) is the Boltzmann constant and \( T \) is the temperature. The distance traveled by electrons while losing energy equal to \( (E_t - 3E_p) \) can easily be calculated using eqn. (6.2) and knowing the optical phonon mean free path \( \lambda_0 \).

Following Koenings theory (26) of hot electron interaction to acoustical phonons, the energy loss per collision to acoustic modes can be written as

\[ \Delta E_a = \frac{4m^*E_s^2}{KT} E_i \]  \hspace{1cm} \text{(6.3)}
where $m^\ast$ is the effective electron mass, $C_S$ is the velocity of sound in GaAs, and $E_i$ is the electron energy at which interaction with acoustical phonons is initiated and it is equal to $3E_p$ in the present case. Using eqn. (6.3), an expression for a mean number of collisions required by a carrier to lose its energy from $3E_p$ to $\phi_2$ can be obtained as

$$n = \frac{\ln(3E_p/\phi_2)}{\ln\left(\frac{1}{1 - \frac{4m^\ast C_S^2}{KT}}\right)} \quad (6.4)$$

where $\phi_2$ is the energy equivalent to the high-low barrier height which an electron is required to retain to overcome the barrier and is given by eqn. (6.1).

The distance traversed by the carriers to lose energy equal to $(3E_p - \phi_2)$ can be obtained by using Gossicks' (27) expression

$$L_a = \lambda_\alpha \sqrt{n/3} \quad (6.5)$$

where $\lambda_\alpha = \lambda_0 (4.18/T)$ is the acoustical phonon mean free path (5, 24).

With $E_t$ as a variable parameter and values of constants listed in Table 6-1, lengths for optical and acoustical losses are calculated using eqns. (6.2 to 6.6). The results are presented in Fig. 6.1. The horizontal lines in the figure correspond to high-low barrier height for bulk dopings (from eqn. 6.1) indicated there and the $K_T$ line represents the room temperature (300 K) thermal energy level. The results show that the interaction with polar optical
TABLE 6 - I
NUMERICAL VALUES OF CONSTANTS FOR GaAs AT 300K

<table>
<thead>
<tr>
<th>CONSTANTS</th>
<th>VALUE</th>
<th>REF.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_p$</td>
<td>0.035 eV</td>
<td></td>
</tr>
<tr>
<td>$\lambda_0$</td>
<td>40 Å</td>
<td>25</td>
</tr>
<tr>
<td>$m^*$</td>
<td>0.072 $m_0$</td>
<td></td>
</tr>
<tr>
<td>$C_S$</td>
<td>$5.54 \times 10^3$ m/sec.</td>
<td>33</td>
</tr>
</tbody>
</table>

TABLE 6 - II
OPTIMUM WIDTH OF UPDEPLETED $n^+$ - REGION
FOR ELECTRON ENERGY OF 0.4 eV

<table>
<thead>
<tr>
<th>BULKDOPING $N_B$ ($cm^{-3}$)</th>
<th>HIGH - LOW BARRIER HEIGHT $\Phi_2$ (eV)</th>
<th>UNDEPLETED $n^+$ REGION WIDTH $\sigma$ Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{14}$</td>
<td>0.22</td>
<td>360</td>
</tr>
<tr>
<td>$10^{15}$</td>
<td>0.16</td>
<td>480</td>
</tr>
<tr>
<td>$10^{16}$</td>
<td>0.10</td>
<td>600</td>
</tr>
<tr>
<td>$10^{17}$</td>
<td>0.04</td>
<td>1300</td>
</tr>
</tbody>
</table>
FIG. 6.1 HOT ELECTRON ENERGY IN NEUTRAL n⁺ REGION LENGTH.
phonons is very efficient in relaxing the energy of hot carriers, whereas it is far slower for acoustical modes. This is in agreement with the theoretical prediction of Evard (19).

In Fig. 6.2, the optimum length $L_B$, of the $n^+$ region vs semiconductor bulk doping $N_B$ are plotted for hot electrons energy varying from 0.1 to 0.5 eV. This provides the maximum thickness of undepleted part of the $n^+$ region, which a hot carrier can travel and at least retains the energy equal to $\phi_2$, so that it can circumvent the high-low barrier. The data from this figure are tabulated in Table 6 - II for electrons of energy $E_c = 0.4$ eV. The optimum length of the $n^+$ region may then be obtained by adding the metal - $n^+$ barrier width to fabricate extremely low resistance contacts by implantation or molecular beam epitaxy.

The available measured values of $n^+$ - layer thickness, in the literature (28-32) are also marked in the Fig. 6.2. The contact resistivity reported for these lies in the range of $10^{-6} - 10^{-7}$ ohm - cm$^2$. The comparison of measured values with the theoretical curves in the figure suggests that the thickness of the $n^+$ layer should be reduced further to ameliorate the contacts.

6.5 DISCUSSIONS

Based on the interaction of hot electrons with polar optical and acoustical phonons, the study provides the optimum length of the $n^+$ - intermediate layer of a metal - $n^+$ - n GaAs ohmic structure. The electron tunneling across the M-S junction predominantly loses energy via these modes while traversing the $n^+$ - region and still retains sufficient energy to surmount the high - low barrier, which
FIG. 6.2 DEPENDENCE OF OPTIMUM LENGTH ($L_B$) OF NEUTRAL $n^+$ REGION ON BULK DOPING ($N_B$). NUMBERS IN THE INSERT IDENTIFY THE REFERENCE NUMBER OF THE CITED POINT.
has been found to limit the contact resistance (7, 8, 33) of such an ohmic structure (8). Thus, the results provide an important design criterion to ameliorate ohmic contacts to n-GaAs.

However, the theory assumes that electrons which have enough energy to cross the high-low barrier do not return back into the base and those which have not enough energy to surmount the barrier are reflected specularly back into the n⁺-region. However, these are not true in actual fact, but are neglected to avoid complexity (11, 15). We believe this does not cause much error as agreement between experimental and theoretical data in fig. 6.2 appears reasonably good.

6.6 CONCLUSIONS

Discussions in the preceding sections conclude that the design of an ohmic contact is primarily based on doping and thickness of the intermediate n⁺-region, since as far as a contact designer is concerned Φ₁ & Φ₂ are constant. The optimization of the n⁺-region thickness follows carrier energy loss criteria as computed in the previous section. However, the doping in the n⁺-region involves technological deliberations and are required to be manœuvred to minimise the contact resistance.

According to our gallium vacancy model, for alloyed contacts, the doping at the M-S interface is restricted by limited amount of available gallium vacancies. About 80% of these are consumed in the formation of neutral pairs GeGaGeAs and only 10% gives donors. To restrict the formation of neutral pairs, the generation
of acceptors i.e. Ge$_{\text{As}}^-$ should be minimised and this can be achieved by preventing arsenic loss from the GaAs which give rise to arsenic vacancies for acceptor formation by germanium substitution.

The improvement in the resistance value by transient annealing techniques and alloying with an encapsulant layer or under arsenic pressure is most likely attributed to this affect (2-4 ). Further improvements may not be possible unless some exotic means are incorporated in alloying technology to enhance the formation of donors Ge$_{\text{Ga}}^+$. For an example, on basis of characterisation results in the chapter II it can be proposed that the inclusion of an appropriate amount of gallium in the metallization may produce desired density of gallium vacancy for donors, without arsenic evolution. This may be one of the possible ways to prohibit formation of acceptors & neutral complexes in the semiconductor surface underneath the contacting metal.

For low resistance implanted or epitaxial contacts, the high - low barrier model described in the chapter IV demonstrates that the contact resistance is tunneling dependent for $N_B \gg N_C$ and to obtain resistivity better than $10^{-7}$ ohm - cm$^2$, carrier concentration in the interfacial layer should exceed $10^{20}$ cm$^{-3}$. For lightly doped substrates (i.e. $N_B < N_C$) the contact resistance is limited by high – low barrier impedance and even a very high doping in the n$^+$ - intermediate region does not reduce the resistance. Therefore, n$^+$ region should be doped only to a level such that metal - n$^+$ tunnelling junction resistance is negligible compared to that of the high - low barrier. Hence the model predicts that it is unnecessary to dope the intermediate region above an optimum level. The Table-4-I provides such a data for n-GaAs contacts.
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