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Mobility analysis in AlGaN channel HEMT

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1 Electron mobility analysis from scattering mechanism

1.1 Alloy disorder scattering

In AlGaN channel HEMTs, both the channel and barrier layers are composed of the $Al_xGa_{1-x}N$ alloy. Due to the mixed composition of aluminum (Al) and gallium (Ga) in these layers, the 2DEG experiences scattering caused by the random distribution of alloy constituents in the lattice.

In this analysis, we consider the contributions to alloy disorder scattering from two distinct sources:

- **Alloy Disorder Scattering from the Channel:** This refers to the scattering experienced by the 2DEG within the $Al_xGa_{1-x}N$ channel layer itself, where the electron mobility is directly affected by the disorder in the alloy composition.

- **Alloy Disorder Scattering from Barrier Penetration:** This accounts for the scattering caused by the penetration of the 2DEG wavefunction into the barrier layer, where the compositional fluctuations in the $Al_xGa_{1-x}N$ barrier layer contribute to additional scattering effects.

First of all to extract the 2DEG distribution in the well (channel) and barrier, we will consider the modified Fang-Howard wavefunction which can be used to determine the distribution of 2DEG with sufficient accuracy. The modified Fang-Howard wavefunction is given by [1] [2]:

$$\chi(z) = \begin{cases} M e^{\frac{\kappa_b z}{2}}, & z < 0 \\ N(z + z_0) e^{\frac{-bz}{2}}, & z \geq 0 \end{cases} \tag{1}$$

where, $\kappa_b = \dfrac{2}{\hbar}\sqrt{2m_y^\star \Delta E_c(x)}$ is the wavevector characterizing the penetration into the barrier, $\Delta E_c(x)$ is conduction offset between the $Al_yGa_{1-y}N$ barrier layer and $Al_xGa_{1-x}N$ channel layer. M and N are normalization constant, z_0 is a constant and b is a variational parameter, chosen such that it minimizes the energy. For, the wavefunction given by eq. 1, we cannot obtained an analytical solution of b. However, if the penetration probability into barrier is small, then good starting guess of b will be $b \approx \left[\dfrac{33m^\star e^2 n_s}{8\hbar^2 \epsilon_0 \epsilon_r}\right]^{1/3}$, where n_s is 2DEG density [3]. This b minimizes the energy in case of Fang-Howard wavefunction where it is assumed that penetration in barrier is zero.

Now, $\chi(z)$ and $\dfrac{1}{m^\star(z)}\dfrac{d\chi(z)}{dz}$ at $z = 0$, we get

$$\begin{aligned}\chi(0) = Me^{\frac{\kappa_b \cdot 0}{2}} &= N(0+z_0)e^{\frac{-b\cdot 0}{2}} \\ \implies M &= Nz_0\end{aligned} \tag{2}$$

and,

$$\begin{aligned}\frac{1}{m^\star(0)}\frac{d\chi(z)}{dz}\bigg|_{z=0} &= \frac{1}{m^\star(0^-)}\frac{M\kappa_b}{2} = \frac{1}{m^\star(0^-)}N(1-\frac{z_0 b}{2}) \\ \implies \frac{1}{m_y^\star}\frac{Nz_0\kappa_b}{2} &= \frac{1}{m_x^\star}N(1-\frac{z_0 b}{2}) \\ \implies \frac{1}{m_y^\star}\frac{Nz_0\kappa_b}{2} &= \frac{N}{m_x^\star}(1-\frac{z_0 b}{2}) \\ \implies \frac{m_x^\star}{m_y^\star}\frac{z_0\kappa_b}{2} &= 1-\frac{z_0 b}{2} \\ \implies \frac{m_x^\star}{m_y^\star}\frac{z_0\kappa_b}{2} + \frac{z_0 b}{2} &= 1 \\ \implies \frac{z_0}{2}\left[\frac{m_x^\star}{m_y^\star}\kappa_b + b\right] &= 1 \\ \implies z_0 &= \frac{2}{\frac{m_x^\star}{m_y^\star}\kappa_b + b}\end{aligned} \tag{3}$$

Now we till take the account of normalization conditions,

$$\begin{aligned}\int_{-\infty}^{\infty}|\chi(z)|^2 dz &= 1 \\ \implies \int_{-\infty}^{\infty}|\chi|^2 = \int_{-\infty}^{0}|Nz_0 e^{\frac{\kappa_b z}{2}}|^2 dz &+ \int_{0}^{\infty}|N(z+z_0)e^{\frac{-bz}{2}}|^2 = 1 \\ \implies N^2 z_0^2\int_{-\infty}^{0} e^{\kappa_b z}|^2 dz &+ N^2\int_{0}^{\infty}(z+z_0)^2 e^{-bz} = 1 \\ \implies N &= \sqrt{\frac{b^3}{2}}\frac{1}{\left[1+bz_0+\frac{b^2 z_0^2}{2}\left(1+\frac{b}{\kappa_b}\right)\right]^{1/2}}\end{aligned} \tag{4}$$

Referring to equation (110) in the work of Bastard [2], the inverse of the scattering time can be written as:

$$\frac{1}{\tau_{\text{alloy}}} = m^\star \frac{\Omega_o}{\hbar^3}[\delta V]^2 x(1-x)\int_{\mathcal{L}} dz\chi^4(z) \tag{5}$$

where, $\mathcal{L}$ is macroscopic length in ternary material with alloy fraction given as x, δV is alloy scattering potential and Ω_o is volume of the lattice.

1.1.1 Alloy disorder scattering from channel

Let us consider that the aluminum (Al) fraction is x. Then,

$$\begin{aligned}
\frac{1}{\tau_{\text{alloy}}} &= m_x^\star \frac{\Omega_o}{\hbar^3}[\delta V]^2 x(1-x)\int_{\mathcal{L}} dz\chi^4(z) \\
&= m_x^\star \frac{\Omega_o}{\hbar^3}[\delta V]^2 x(1-x)\int_0^\infty dz\left(N(z+z_0)e^{\frac{-bz}{2}}\right)^4 \\
&= m_x^\star \frac{\Omega_o}{\hbar^3}[\delta V]^2 x(1-x)\mathcal{I}
\end{aligned} \tag{6}$$

where,

$$\mathcal{I} = \frac{N^4}{4b^5}\left[2b^4z_0^4 + 4b^3z_0^3 + 6b^2z_0^2 + 6bz_0 + 3\right] \tag{7}$$

$\therefore$,

$$\mu_{\text{alloy\_channel}} = \frac{e}{(m_x^\star)^2}\frac{\hbar^3}{\Omega_o[\delta V]^2 x(1-x)\mathcal{I}} \tag{8}$$

If we consider that barrier penetration is insignificant [4], the wavefunction can be approximated using the Fang-Howard wavefunction, which is given as:

$$\chi(z) = \begin{cases} 0 & z < 0 \\ \sqrt{\dfrac{b^3}{2}}ze^{\frac{-bz}{2}} & z \geq 0 \end{cases} \tag{9}$$

and thus,

$$\begin{aligned}
\frac{1}{\tau_{\text{alloy}}} &= m_x^\star \frac{\Omega_o}{\hbar^3}[\delta V]^2 x(1-x)\int_{\mathcal{L}} dz\chi^4(z) \\
&= m_x^\star \frac{\Omega_o}{\hbar^3}[\delta V]^2 x(1-x)\frac{3b}{16}
\end{aligned} \tag{10}$$

$\therefore$,

$$\mu_{\text{alloy\_channel}} = \frac{e\hbar^3}{(m_x^\star)^2\Omega_o[\delta V]^2 x(1-x)}\frac{16}{3b} \tag{11}$$

and $b = \left[\dfrac{33m_x^\star e^2 n_s}{8\hbar^2\epsilon_0\epsilon_s}\right]^{1/3}$ minimizes the energy.

1.1.2 Alloy disorder scattering from barrier penetration

Let us consider that the aluminum (Al) fraction in barrier is y. Then,

$$\begin{aligned}\frac{1}{\tau_{\text{alloy}}} &= m_y^\star \frac{\Omega_o}{\hbar^3}[\delta V]^2 y(1-y)\int_{\mathcal{L}} dz\chi^4(z) \\ &= m_y^\star \frac{\Omega_o}{\hbar^3}[\delta V]^2 y(1-y)\int_{-\infty}^{0} dz(Me^{\frac{\kappa_b z}{2}})^4 \\ &= m_y^\star \frac{\Omega_o}{\hbar^3}[\delta V]^2 y(1-y)\frac{M^4}{2\kappa_b}\end{aligned} \tag{12}$$

From eq. 1, the penetration probability in barrier will be given as:

$$P_b = \int_0^{-\infty} dz|Me^{\frac{\kappa_b z}{2}}|^2 = \frac{M^2}{\kappa_b} = \frac{N^2 z_0^2}{\kappa_b} \tag{13}$$

By substituting, eq. 12 and 13 in expression of mobility, then we will get mobility as:

$$\mu_{\text{alloy\_barrier}} = \frac{e\hbar^3}{(m_y^\star)^2\Omega_o[\delta V]^2 y(1-y)} \cdot \frac{2}{\kappa_b P_b^2} \tag{14}$$

In our case, since an AlN interlayer is present between the channel and the barrier, equation 1 is modified for $z < 0$, resulting in a significant reduction in penetration. Consequently, we use BandEng to solve the Schrödinger-Poisson equation and determine the penetration probability P_b [5].

1.1.3 Calculation of Total Mobility Due to Alloy Disorder Scattering

The total mobility due to alloy disorder scattering is calculated using Matthiessen's rule as:

$$\frac{1}{\mu_{\text{alloy}}} = \frac{1}{\mu_{\text{alloy\_channel}}} + \frac{1}{\mu_{\text{alloy\_barrier}}} \tag{15}$$

1.2 Optical phonon scattering

1.3 Interface roughness scattering

1.4 Background impurities scattering

1.5 Dislocation scattering

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1.6 Remote ionization impurities scattering

1.6.1 Barrier

1.6.2 Buffer

References

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