Essentials of MOSFETs

Lecture 5.3: High Electron Mobility Transistors (HEMTs)

Short Problem

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Very high electron mobilities have been achieved in modulation doped structures at low temperatures:

> G. C. Gardner, S. Fallahi, J. D. Watson, and M. J. Manfra, "Modified MBE hardware and techniques and role of gallium purity for attainment of two dimensional electron gas mobility > 35 x 10^6 cm^2/V s in AlGaAs/GaAs quantum wells grown by MBE," *Journal of Crystal Growth*, **441**, 71–77, (2016).

For room temperature, we have a simple prescription for estimating the mean-free-path for backscattering from the measured mobility. For low temperatures, the non-degenerate expressions we have been using in these lectures need to be replaced by fully degenerate (T = 0 K) expressions. A brief summary follows.

The Fermi velocity is

$$\upsilon_F = \sqrt{\frac{2\left(E_F - E_C\right)}{m^*}} \quad . \tag{1}$$

The 2D electron density is

$$n_S\left(0\text{ K}\right) = \frac{m^*}{\pi\hbar^2}\left(E_F - E_C\right)\text{ cm}^{-2} . \tag{2}$$

The conductance at T = 0 K is

$$G\left(0\text{ K}\right) = \frac{2q^2}{h}\mathcal{T}\left(E_F\right)M\left(E_F\right) = \frac{2q^2}{h}\frac{\lambda\left(E_F\right)}{L}M\left(E_F\right), \tag{3}$$

where the last expression on the RHS assumes the diffusive limit. We can evaluate the sheet conductance (the 2D conductivity) from

$$G = \sigma_S\frac{W}{L} \rightarrow \sigma_S = G\frac{L}{W} = \frac{2q^2}{h}\lambda\left(E_F\right)M\left(E_F\right)/W \quad . \tag{4}$$

Using

$$M\left(E_F\right)/W = \frac{\sqrt{2m^*\left(E_F - E_C\right)}}{\pi\hbar}, \tag{5}$$

in (4), we find

$$\sigma_S(0\text{ K}) = \frac{2q^2}{h}\lambda(E_F)\frac{\sqrt{2m^*(E_F - E_C)}}{\pi\hbar}. \tag{6}$$

Now, defining the mobility by

$$\sigma_S(0\text{ K}) \equiv n_S(0\text{ K})q\mu_n(0\text{ K}) \tag{7}$$

we can use (6) and (7) with (1) and (2) to find

$$\mu_n(0\text{ K}) = \left[\frac{\lambda(E_F)\upsilon_F}{2}\right]\frac{1}{(E_F - E_C)/q}. \tag{8}$$

Finally, we recognize the quantity in brackets as the diffusion coefficient at T = 0 K,

$$D_n(0\text{ K}) = \left[\frac{\lambda(E_F)\upsilon_F}{2}\right]. \tag{9}$$

Using (8) and (9), we can also write

$$\frac{D_n(0\text{ K})}{\mu_n(0\text{ K})} = \frac{(E_F - E_C)}{q} \quad , \tag{10}$$

which looks like a generalization of the Einstein relation to T = 0 K.

To see if you have followed the above train of thought, answer the following question.

1) Gardner *et al.* report a mobility of $35\times10^6\text{ cm}^2/\text{V-s}$ at a carrier density of $n_S = 3\times10^{11}\text{ cm}^{-2}$. What is the mean-free-path for backscattering in this sample? Assume an effective mass of $0.067m_0$