SUPPLEMENTAL ONLINE MATERIALS

Profiling the Thermoelectric Power of Semiconductor Junctions with Nanometer Resolution

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Materials and Methods

Experimental procedure

Our samples were GaAs multiple *p-n* junctions grown by molecular beam epitaxy (MBE). The samples were cleaved in-situ in the UHV STM chamber to expose the cross sectional surface for measurement. The tip-sample contact was realized by the following procedure. At each point, after a tip-sample gap of about 1 nm or less was stabilized by the STM feedback loop, the control loop was interrupted and the STM bias was set to zero. The tip and the sample were then connected to an electrometer with input impedance larger than 10^{13} Ω. Subsequently, the tip was moved step-by-step toward the sample at about 0.5-1 Å/step. A large fluctuation in the measured voltage was observed before the tip contacted the sample. As the tip made a nano-contact with the sample, the voltage signal became stable as the tip was moved vertically down and up by about 1 Å. After the thermoelectric voltage was measured at each point, the sample was scanned to obtain a STM topographic image in order to verify that the lateral drift of the image was smaller than 1 nm.

Calculation procedure

In a p-n junction, both majority and minority carriers contribute to the Seebeck coefficient (S) (*1,2*), i.e.

$$S = \frac{n\mu_n S_n + p\mu_p S_p}{n\mu_n + p\mu_p} \tag{1}$$

where n and p are electron and hole concentrations, respectively, S_n and S_p the Seebeck coefficient of electrons and holes, respectively, and μ_n and μ_p the mobility of electrons and holes, respectively. For the case that one carrier concentration is much higher than the other, S reduces to either S_n or S_p depending on the majority carrier type. The Boltzmann Transport Equation has been used to obtain the following expressions (*3*)

$$S_n = \frac{k_B}{e}\left[\eta - \frac{(r_e + \frac{5}{2})F_{r_e+\frac{3}{2}}(\eta)}{(r_e + \frac{3}{2})F_{r_e+\frac{1}{2}}(\eta)}\right]; \eta = \frac{E_F - E_c}{k_B T} \tag{2a}$$

and,

$$S_p = \frac{k_B}{-e}\left[\eta - \frac{(r_v + \frac{5}{2})F_{r_v+\frac{3}{2}}(\eta)}{(r_v + \frac{3}{2})F_{r_v+\frac{1}{2}}(\eta)}\right]; \eta = \frac{E_v - E_F}{k_B T} \tag{2b}$$

where $F_m(\xi) \equiv \int_0^\infty \frac{x^m dx}{e^{(x-\xi)} + 1}$ is the Fermi-Dirac integral of order m, E_c and E_v the conduction and valence band edges, E_F the Fermi level, k_B the Boltzman constant, e the electron charge, and r_e and r_h the scattering parameters for electrons and holes defined in terms of the respective scattering mean free times (τ_e and τ_h) by $\tau_e \propto (E - E_c)^{r_e}$ and $\tau_h \propto (E_v - E)^{r_h}$. For a semiconductor such as GaAs, typically $r_e = r_h$

= 1/2 at a temperature much lower than the Debye temperature. For non-degenerate semiconductors where η>-3, two simplified equations can be obtained as

$$S_n = \frac{1}{-eT}\left[E_C - E_F + (\frac{5}{2} + r_e)k_B T\right] = -\frac{k_B}{e}\left[\ln\frac{N_c}{n} + (\frac{5}{2} + r_e)\right] < 0 \qquad (3a)$$

and,

$$S_p = \frac{1}{eT}\left[E_F - E_V + (\frac{5}{2} + r_h)k_B T\right] = \frac{k_B}{e}\left[\ln\frac{N_v}{p} + (\frac{5}{2} + r_h)\right] > 0 \qquad (3b)$$

These three equations were used for calculating the *S* profile across the *p-n* junction from the dopant profile, and for obtaining the band structure and carrier concentrations from the measured *S*.

References

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