半導体二重障壁ヘテロ構造熱電子放出冷却構造中の電子温度

Electron temperature in semiconductor double barrier thermionic cooling heterostructures

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Managing rapid increase in thermal power densities associated with device miniaturization is a major technological challenge. Development of new efficient cooling technologies is therefore urgently required for future progress in electronics. Solid-state cooling devices can be one answer, owing to their high efficiency and compatibility for integration. To achieve efficient cooling, we have been working on semiconductor double barrier heterostructures to utilize the thermionic cooling effect [1], as shown in Fig. 1(a). In the present heterostructure, cold electrons are first injected into the quantum well (QW) by resonant tunneling through the thin barrier (emitter barrier). Subsequently, hot electrons are removed by thermionic emission over the second thick barrier (collector barrier). This sequential two-step conduction process is essential for the cooling effect. To quantitatively understand the conduction process, we have developed an analytical theory to calculate the two-step current and compared it with experiment [2]. In this work, we have considered not only the current flow but also the energy balance in the electron system in the QW:

$$< \frac{dE}{dt} >= \frac{<k_B T_e> - <k_B T_l>}{\tau_e} = \frac{P}{n} \qquad (1)$$

Here, the cooling power P is calculated from analytical theory [2], k_b the Boltzmann constant, T_e and T_l are the temperature of electron and lattice systems, respectively, τ_e is the energy relaxation time, and n is the density of electrons in the QW. The electron temperature in the QW can be calculated and compared with experimental data.

To clarify the electron cooling behavior, we have measured voltage-dependent photoluminescence (PL) spectra on a sample shown in Fig. 1(a). The high-energy tail of the PL spectra reflects the electron distribution function, from which we can determine Te. In Fig. 1(b), the black dotted curve shows voltage-dependent T_e in the QW. Cooling starts after V is applied and T_e reaches its minimum (~262 K) when V ~ 0.5 V. For $V >$ 0.6 V, T_e gradually increases with V. In Fig. 1(b), T_e calculated by Eq. (1) is also plotted in red. In the calculation, we assumed τ_e to be 0.1 ps. The calculated result gives reasonable accounts for the experiment. We will discuss more detail at the conference.

References [1] A. Yangui, M. Bescond, T. Yan, N. Nagai, K. Hirakawa, Nature Commun. **10,** 4504 (2019).
[2] X. Zhu, M. Bescond, G. Bastard, K. Hirakawa, et al., Phys. Rev. Appl. 16, 064017 (2021).

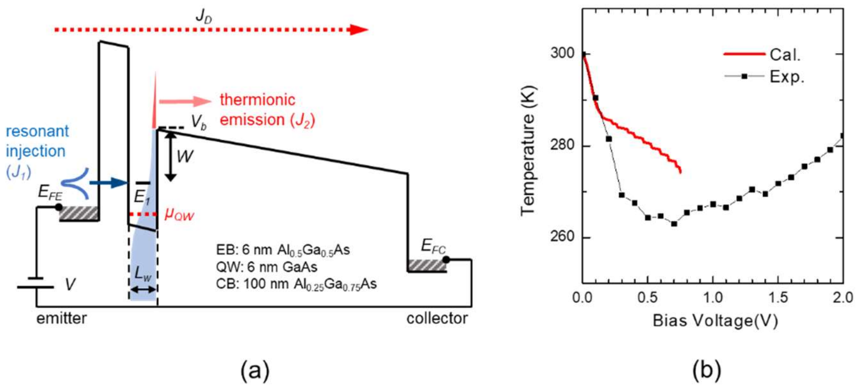

Fig. 1 (a) Band diagram of the double barrier thermionic cooling structure, (b) electron temperature as a function of applied voltage.