Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp1019-1020

Thermionic cooling device based on asymmetric double-barrier heterostructure

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Abstract

We report a semiconductor cooling device based on an asymmetric AlGaAs/GaAs double barrier resonant tunneling heterostructure, using the concept of thermionic cooling. Electron temperatures, Te, in the quantum well (QW) and in the electrodes were determined by photoluminescence (PL) measurements. We have found that Te in the QW decreases from 300 K down to 250 K as the bias voltage, V, is increased from 0 to ~ 0.5 V, which corresponds to the resonant tunneling condition, deduced from the current-voltage (I-V) measurements. In contrast, Te in the electrodes is unchanged. The experimental result is in reasonable agreement with theory and clearly demonstrates the thermionic refrigeration effect in semiconductor heterostructures.

1. Introduction

Managing rapid increase in thermal power densities associated with electronic miniaturization is a major technological challenge [1]. Development of new efficient cooling technologies is therefore urgently required for future progress in electronics. In 2005, K.A. Chao *et al*. [2] proposed a possibility of thermionic cooling effect by using an AlGaAs/GaAs asymmetric double barrier heterostructure.

Here, we have investigated experimentally and theoretically an AlGaAs/GaAs asymmetric double barrier heterostructure proposed in Ref. [2] and demonstrated cooling of electrons in the QW as much as 50 K at 300 K.

2. Experimental

The sample was prepared by molecular beam epitaxy (MBE) on a n-type GaAs substrate by growing successively a 300 nm-thick n^+-GaAs (Si: $1x10^{17}$ cm^{-3}), a 5 nm-thick GaAs buffer layer, a 15 nm-thick $Al_{0.4}Ga_{0.6}As$ barrier, 4 nm-thick GaAs QW, 100 nm-thick $Al_{0.25}GaAs_{0.75}As$ barrier, 50 nm-thick GaAs, and finally, 10 nm-thick n^+-GaAs (Si: $7x10^{18}$ cm^{-3}) for good ohmic contact. The device was then patterned into a 200 μm x 200 μm mesa. Ni/AuGe/Au contacts were deposited on the front and back sides of the wafer and annealed at 450°C.

Figure 1 illustrates the band diagram and the working principle of the heterostructure thermionic cooling device. The electron transport in this structure is due to resonant tunneling and subsequent thermionic emission; under an appropriate bias voltage, cold electrons are first injected into the QW by resonant tunneling through an injector thin barrier. Electrons are then thermalized in the QW and subsequently removed from the QW by thermionic emission over a thicker potential barrier. This rather simple electronic transport process efficiently removes heat from the QW and works as a refrigerator.

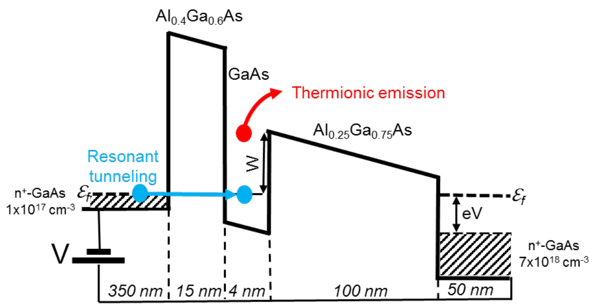

Fig. 1 Potential profile of the GaAs/AlGaAs double barrier thermionic cooling structure.

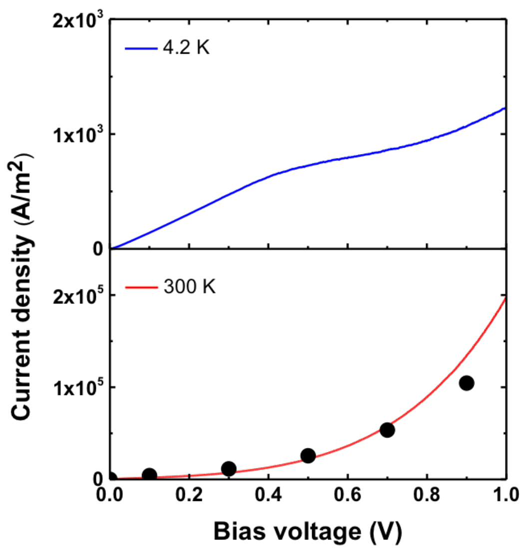

Fig. 2 Current density J as a function of the bias voltage V measured at 4.2 K (top panel) and 300K (solid line in bottom panel), showing a good agreement with the quantum transport simulation results (black symbols).

Samples were characterized by the I-V measurements. Figure 2 shows the electron current density J as a function of the applied bias V measured at 4.2 K and 300 K. From low temperature measurements, the resonant tunneling shoulder can be clearly identified around ~ 0.5 V, while this later is smoothed at room temperature by the thermal current component. We also see that high temperature J-V measurement shows an excellent agreement with our quantum transport simulations [3].

To determine the electron temperatures, Te, in the QW and in the electrodes, we used PL spectroscopy. Figure 3(a) shows room temperature PL spectra of the AlGaAs/GaAs heterostructure measured at various V, and under a 2.54 eV laser excitation. We identified a first broad PL peak at 1.426 eV resulting from the Si-doped GaAs electrodes layer's emission, and a shaper PL peak at 1.552 eV accompanied with a shoulder at 1.578 eV. These last two peaks originate from the radiative recombination of electrons with heavy holes (HH), and electrons with light holes (LH) respectively. By assuming the Maxwell-Boltzmann distribution for electrons, we deduced Te from the high-energy tails of the PL peaks [5]. Electron temperature in the QW first continuously decreases with the applied bias, reaching 250 K at 0.5 V (Fig. 3(b)). This bias value corresponds to the resonant tunneling condition, as shown experimentally in Fig. 2. Above that voltage, the Te in the QW becomes roughly constant. On the other hand, Te in the highly doped electrode regions is almost bias independent, supporting the reliability of our PL measurement method.

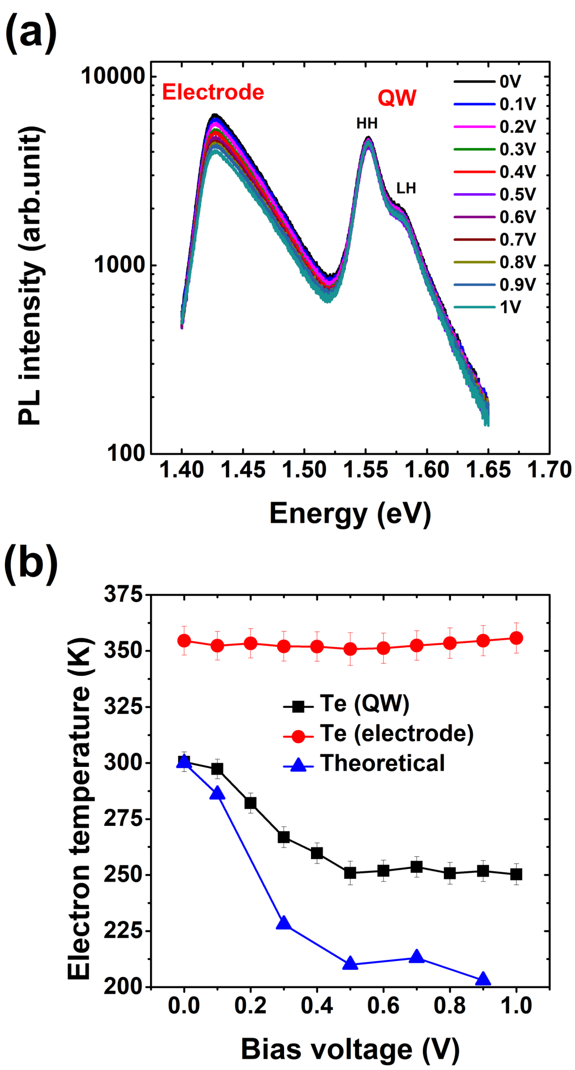

Fig. 3 (a) Room temperature PL spectra measured under 2.54 eV laser irradiation and at various bias voltages, showing the emission from the electrodes and the QW. (**b**) Experimental electron temperatures as a function of *V*, in the QW (black squares) and the electrodes (red circles). Blue triangles represent the simulated electron temperatures in the QW.

To understand this behavior, we have performed full quantum simulations, which took into account the coupling between electronic and thermal currents by self-consistently solving the transport equations within the non-equilibrium Green's function (NEGF) framework and the heat equation [3]. The results predict a significant drop in Te (~ 70 K) at 300 K in the QW (see Fig. 3(b)). The experimental result is found to be in reasonable agreement with theory, clearly demonstrating the thermionic refrigeration effect in semiconductor heterostructures.

3. Conclusions

We investigated the cooling properties of an asymmetric double barrier thermionic cooling device. Electron temperatures, Te, in the QW and in the electrodes were measured based on a refined analysis of PL spectroscopy. We found that Te in the QW decreases with the applied bias down to 250 K at V ~ 0.5 V, which corresponds to the resonant tunneling condition. In contrast, Te in the electrode was bias independent, supporting the validity of our measurements. Experimental results were validated by quantum transport simulations, clearly demonstrating the electronic refrigeration character of the considered heterostructure.

Acknowledgements

We gratefully acknowledge the Japan Society for the Promotion of Science (JSPS) for a financial support (16F16783).

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