Diameter dependence of current–voltage characteristics of ultrasmall area AlSb–InAs resonant tunneling diodes with diameters down to 20 nm

K. Nomoto,[a] K. Taira, T. Suzuki, and I. Hase
Sony Corporation Research Center, Hodogaya-ku, Yokohama 240, Japan

H. Hiroshima and M. Komuro
Electrotechnical Laboratory, Ministry of International Trade and Industry, Tsukuba-city, Ibaraki, 305, Japan

(Received 7 October 1996; accepted for publication 10 February 1997)

We have studied the current–voltage characteristics $I(V)$ of ultrasmall area AlSb–InAs resonant tunneling diodes (RTDs) with diameters down to 20 nm. Resonant tunneling peaks were observed for all the diodes at room temperature. The peak-to-valley ratio reduces with the decreasing diameter of the RTD. We found from the diameter dependence of the valley current that the reduction is due to a contribution of the thermally activated surface current to the valley current. For RTDs with diameters less than 100 nm, we observed fine structures around zero bias at 4 K. They can be attributed to tunneling through zero-dimensional states confined by a RTD sidewall. © *1997 American Institute of Physics.* [S0003-6951(97)04015-1]

Reducing the area of vertical semiconductor resonant tunneling diodes (RTDs) is of much interest, because the reduction makes it possible (i) to study single-electron tunneling and the Coulomb blockade effect,[1–3] (ii) to increase the device density on a chip using RTD,[4] and (iii) to reduce the capacitance that determines the cutoff frequency.[5] Up to date, most of the research on small area RTDs has employed an AlGaAs–GaAs material system. However, when the diameter of the AlGaAs–GaAs RTD is reduced to less than 100 nm, the contact layers of the RTD are pinched off by the surface depletion layer induced by the surface Fermi-level pinning in the middle of the band gap of GaAs. For InAs, on the other hand, the surface Fermi level is located just below or above the conduction-band edge and no surface depletion layer exists.[6] Therefore, InAs-based RTDs are expected to have no diameter limitation. Although InAs-based RTDs have been studied for high-frequency application,[5] and to understand the basic physics of tunneling affected by band structure,[7] no attempt to reduce the diameter has been reported. In this letter, we report $I(V)$ characteristics of symmetric AlSb–InAs double-barrier RTDs with diameters down to *20 nm* which is, to our knowledge, the smallest diameter of a RTD that has ever been reported. We will first focus on the diameter dependence of the peak current, the valley current, and the ratio of these currents. There is a debate about the origin of the increasing valley current density observed for smaller area AlGaAs–GaAs RTDs.[2,8] We confirm that for AlSb–InAs RTDs, the surface leakage current is responsible for most of the increase in the valley current density. We also report fine structures due to tunneling through zero-dimensional (0D) states observed in $dI(V)/dV$ curve at 4 K.

The device layer was grown by molecular beam epitaxy at 500 °C on a (001)-oriented 1×10^{18} cm^{-3} S-doped n-InAs substrate. The layer sequence was as follows: (i) 600 nm n-InAs bottom contact layer ($n=1\times10^{17}$ cm^{-3}), (ii) 10 nm InAs spacer layer, (iii) 5 nm AlSb barrier, (iv) 6 nm InAs well, (v) 5 nm AlSb barrier, (vi) 10 nm InAs spacer layer, (vii) 100 nm n-InAs contact layer ($n=8\times10^{17}$ cm^{-3}), and (viii) 330 nm n^+-InAs top contact layer ($n=1\times10^{18}$ cm^{-3}). Silicon was used as the dopant. Layers (ii)–(vi) were undoped. Using electron-beam lithography with a JEOL 50 keV electron-beam exposure system, JBX-6000SA, and polymethylmethacrylate resist, *nonalloy* AuGe/Au Ohmic metallization dots with diameters between 2000 and 20 nm were defined on n^+-InAs top contact. The Ohmic metal served as an etch mask for $SiCl_4$/He reactive ion etching defining the mesas in the epitaxial structure. The diode diameters were measured using a scanning electron microscope. To make contact to the top of the mesa, a planarizing and insulating photoresist was spun on the as-etched sample and then etched back by O_2 plasma etching to expose the

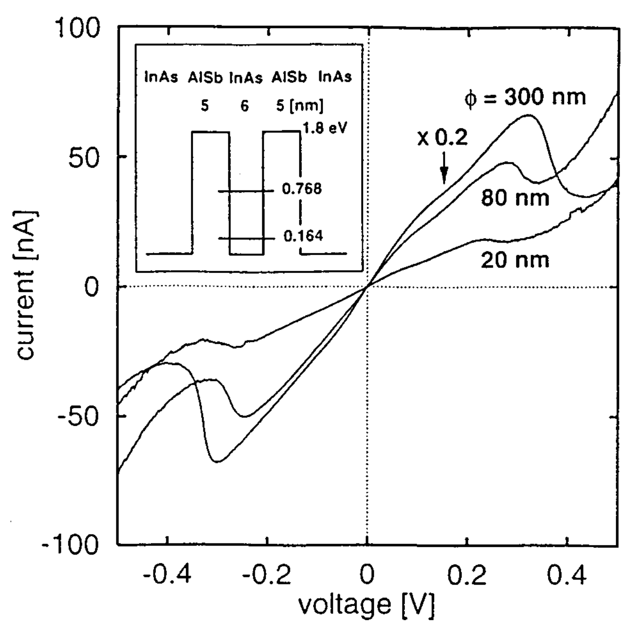

FIG. 1. $I(V)$ curves at room temperature of three RTDs with diameters ϕ of 20, 80, and 300 nm. Inset: Schematic band diagram of the RTD investigated. The 2D-subband energy is obtained from the calculation of the transmission probability for zero bias.

[a]Electronic mail: knomoto@src.sony.co.jp

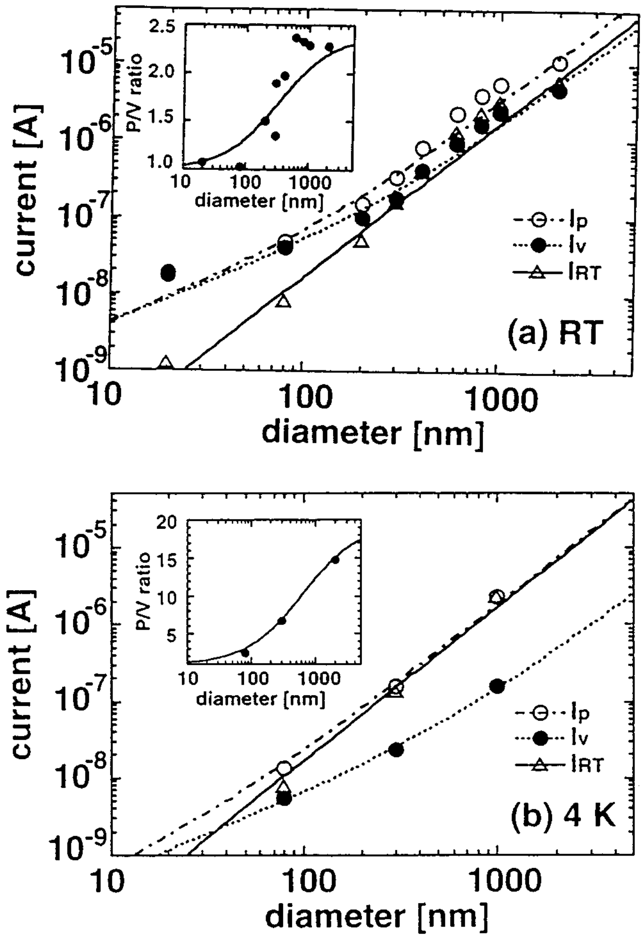

FIG. 2. Peak current (○), valley current (●), and resonant current (△) at room temperature (a) and 4 K (b) as a function of RTD diameters. The best-fitted lines I_{RT}, I_v, and their sum $I_p = I_{\mathrm{RT}} + I_v$ are also shown. Inset: Peak-to-valley ratio as a function of diameters. Solid line is calculated using $(I_{\mathrm{RT}} + I_v)/I_v$.

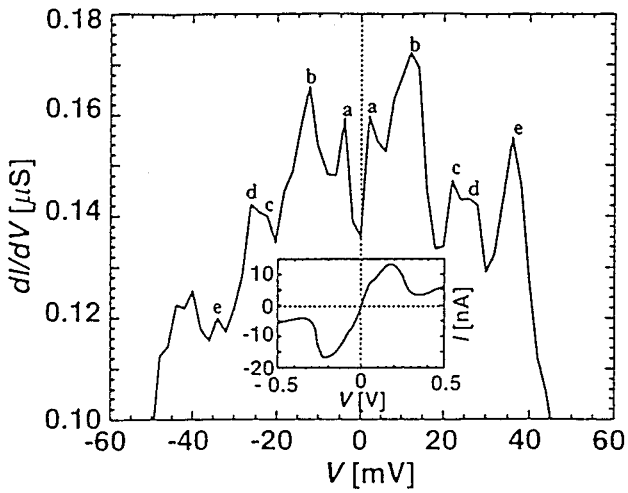

FIG. 3. $I(V)$ and $dI(V)/dV$ curves observed at 4 K of the RTD with a diameter of 80 nm. Fine structures observed at approximately the same absolute voltage are marked with the same letter.

Ohmic metal. A gold contact pad was then evaporated over the top of the mesa.

Figure 1 shows $I(V)$ curves of diodes with diameters of 20, 80, and 300 nm. The voltage is applied to the top contact with respect to the grounded substrate. Current peaks are observed at room temperature for all RTDs. The peaks at $\sim\pm 0.25$ V are caused by resonant tunneling through the lowest two-dimensional (2D) subband in the InAs quantum well. The resonant voltage decreases with decreasing diode diameter, which may be due to a stray series resistance. The ''bumps'' observed at ± 50 mV for all the diodes are interpreted as the tunneling through an InAs Γ-point quasibound state confined by AlSb X-point barriers.[7]

In Fig. 2, we show the diameter dependence of the peak current I_p, the valley current I_v, and the resonant tunneling current defined by $I_{\mathrm{RT}} = I_p - I_v$ at positive bias at room temperature and at 4 K. We observed the same characteristics for negative bias. We found no pinch off diameter for InAs RTDs. The current component I_{RT} is well fitted by the function $I_{\mathrm{RT}} = J_{\mathrm{RT}}(\pi\phi^2/4)$, where $J_{\mathrm{RT}} = 2.1\times 10^6$ A/m^2 irrespective of temperature. Therefore, I_{RT} is attributed to a resonant-tunneling-current component. On the other hand, valley current I_v is fitted by the sum of a bulk current and a surface current, $I_v = J_v(\pi\phi^2/4) + J_s(\pi\phi)$, where $J_v = 1.2\times 10^6$ (9.1×10^4) A/m^2 and $J_s = 4.0\times 10^{-1}(5.7\times 10^{-2})$ A/m at room temperature (4 K). From this, we know that (1) the resonant-tunneling-current density does not reduce with decreasing the diode diameter, (2) not only a bulk current but also a surface current contributes to the valley current, and (3) both the bulk and the surface current are thermally activated. The peak-to-valley (P/V) ratio decreases with decreasing the diode diameter, as shown in the inset of Fig. 2. For AlGaAs–GaAs RTDs, this tendency has been already observed.[2,8] This is due to the increasing valley current density. There is, however, a debate about the origin of the increasing; the weakened lateral-momentum-conservation rule due to the Heisenberg uncertainty principle[2] and surface-related phenomena[8] are topics of discussion. For InAs–AlSb RTDs, we conclude from the results (1), (2), and (3) that *the thermally activated surface current makes the major contribution towards the increasing valley current density*. At the diode sidewall surface, AlSb is damaged by both oxidation and bombardment of ion etchant during the fabrication process, which would cause the midband-gap surface defect levels. Because InAs has an electron accumulating layer at the surface, the hopping through such surface defect levels would contribute to the thermally activated surface current. Surface–phonon scattering can also cause such a surface current.

Figure 3 shows $I(V)$ and $dI(V)/dV$ curves at 4 K for a RTD with a diameter of 80 nm, which is the smallest-diameter RTD that we successfully measured at 4 K. We observed fine structures around zero bias. The fine structures are symmetric in voltage. We have not observed such structures at room temperature or for RTDs with diameters larger than 200 nm. The pattern of the fine structure was reproducible for different samples with the same diameter. We consider that the fine structure is attributed to tunneling through 0D states in an InAs well confined by a RTD sidewall. The spacing between the fine structures is 4–10 mV, which corresponds to 2–5 meV in energy. If we assume that the lateral potential is a square well potential with infinite barrier height and the well width ϕ=80 nm, the energy spacing becomes

$\sim\hbar^2\pi^2/(2m^*_{\mathrm{InAs}}\phi^2)=2.5$ meV. This value is in good agreement with the experimental results. The irregular peak spacing suggests that the lateral potential is not a parabolic potential. This would be because the electrons in InAs are confined not by the surface depletion layer, but abruptly in an insulator.

In summary, the diameter dependence of $I(V)$ characteristics of AlSb–InAs RTDs with diameter down to 20 nm has been studied. The peak-to-valley ratio reduces with decreasing diode diameter. The diameter dependence of the valley current indicates that the reduction is due to the thermally activated surface current. We also observed fine structures around zero bias at 4 K. The sample dependence and the spacing in voltage suggest that they are caused by tunneling through the 0D state confined by an insulator at the diode sidewall.

The authors would like to thank T. Shimada for her technical assistance. The authors are also grateful to J. Westwater for his help in the preparation of the manuscript. This work was performed under the management of FED as a part of the MITI R&D program (Quantum Functional Devices Project) supported by NEDO.

[1] M. A. Reed, J. N. Randall, R. J. Aggarwal, R. J. Matyi, T. M. Moore, and A. E. Wetsel, Phys. Rev. Lett. **60**, 535 (1988).
[2] B. Su, V. J. Goldman, and J. E. Chunningham, Phys. Rev. B **46**, 7644 (1992).
[3] K. Nomoto, T. Suzuki, K. Taira, and I. Hase, Jpn. J. Appl. Phys. 1 **33**, L1142 (1994); Phys. Rev. B **55**, 2523 (1997).
[4] For a review, see *Physics of Quantum Electron Devices*, edited by F. Capasso (Springer, New York, 1990).
[5] L. F. Lio, R. Beresford, and W. I. Wang, Appl. Phys. Lett. **53**, 2320 (1988).
[6] A. G. Milnes and A. Y. Polyakov, Mater. Sci. Eng. B **18**, 237 (1993).
[7] R. E. Carnahan, M. A. Maldonado, K. P. Martin, A. Nogaret, R. J. Higgins, L. A. Cury, D. K. Maude, J. C. Portal, J. F. Chen, and A. Y. Cho, Appl. Phys. Lett. **62**, 1385 (1993).
[8] T. Schmidt, M. Tewordt, R. J. Haug, K. v. Kliting, B. Shönherr, P. Grambow, A. Förster, and H. Lüth, Appl. Phys. Lett. **68**, 838 (1996).