Energy, Electronic device

New methodology of thermoelectric performance enhancement by two-dimensional electron gas

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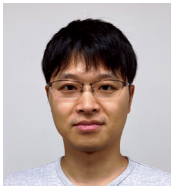

Abstract

Two-dimensional electron gas (2DEG), one of the quantum confinement effects, raises Seebeck coefficient, resulting in ultrahigh thermoelectric power factor. This study demonstrated a new methodology of power factor enhancement using 2DEG with multiple subbands, which is different from conventional 2DEG with one subband. We fabricated triangular quantum well 2DEG (GaAs/InGaAs) with multiple subbands, and this 2DEG exhibited higher Seebeck coefficient because of multiple electron conduction paths with high energy. In addition, modulation doping in the triangular quantum well enhanced the electron mobility. This modulation-doped 2DEG with multiple subbands exhibited 4 times higher increase rate of power factor than the conventional 2DEG with single subband. Stacking this 2DEG with multiple subbands largely enhanced the device output power.

Background & Results

Thermoelectric conversion, which enables us to reuse thermal energy as an electrical energy, is drawing much attention as a renewable energy. The thermoelectric performance is quantified by a dimensionless figure-of-merit: zT; $zT=S^2\sigma T\kappa^{-1}$, where S is Seebeck coefficient, σ is electrical conductivity, κ is thermal conductivity, $S^2\sigma$ is power factor and T is absolute temperature. Nanostructuring approach drastically decreased κ. On the other hand, power factor enhancement is still insufficient. In 1993, Dresselhaus et al theoretically proposed power factor enhancement caused by quantum confinement effect. This quantum confinement effect enhances power factor because of S increase coming from the change of the electronic density-of-states. Previous studies experimentally observed the power factor enhancement in rectangular quantum well 2DEG. However, for further enhancement of power factor, new methodologies beating the conventional quantum confinement effect are demanded. In this study, we proposed a new methodology of power factor enhancement using 2DEG with multiple subbands (Fig. 1b), which is different from the conventional 2DEG with single subband (Fig. 1a). Triangular quantum well has multiple subbands near Fermi level unlike the rectangular one. We experimentally observed S increase caused by multiple electron conduction paths with high energy using GaAs/InGaAs triangular well. As a result, 2DEG with multiple subbands (triangular quantum well) exhibited twice higher power factor than 2DEG with single subband (rectangular quantum well) (Fig. 2). In addition, modulation doping in triangular quantum well also enhanced the electron mobility. This modulation-doped 2DEG with multiple subbands had 4 times higher increase rate of power factor than the conventional 2DEG with single subband. Furthermore, stacking this 2DEG with multiple subbands largely enhanced the device output power, the value of which was higher than those of other film thermoelectric generator.

Significance of the research and Future perspective

We found new methodology of thermoelectric power factor enhancement bringing 4 times higher increase rate of power factor than the conventional quantum confinement effect. This methodology will attract much scientific attention as the effective method to bring a drastic enhancement of thermoelectric performance. The thermoelectric generator composed of stacked 2DEG with multiple subbands will be applied to our society as the power source, which runs IoT sensors, etc.

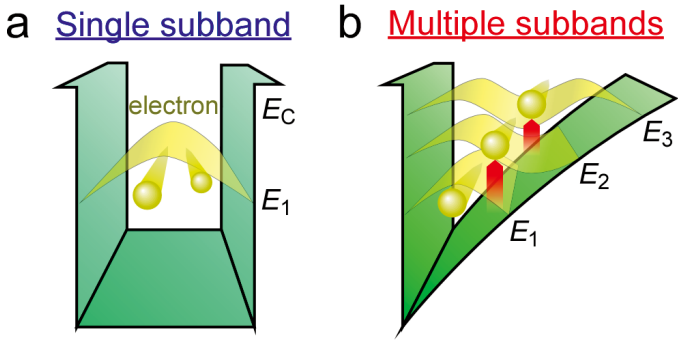

Fig. 1 a 2DEG of rectangular quantum well with single subband.
b 2DEG of triangular quantum well with multiple subbands.
Number of subbands enables us to enhance thermoelectric power factor.

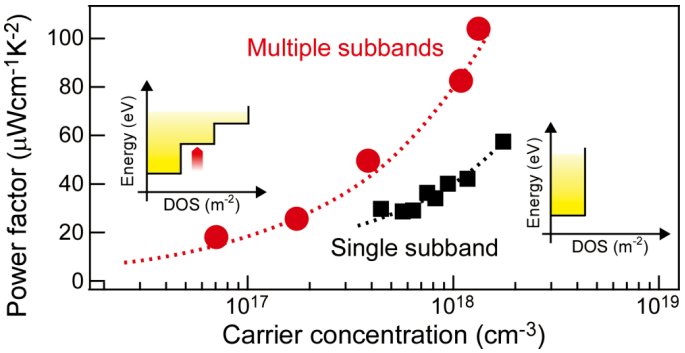

Fig. 2 Carrier concentration dependences of power factor in 2DEG with multiple subbands (solid circle) and single subband (solid square).
Multiple subbands enhanced thermoelectric power factor.

Patent	PCT/JP2025/000606
Treatise	Uematsu, Yuto; Ishibe, Takafumi; Mano, Takaaki et al. Anomalous enhancement of thermoelectric power factor in multiple two-dimensional electron gas system. Nature Communications. 2024, 15, 322. doi: 10.1038/s41467-023-44165-3 Uematsu, Yuto; Ishibe, Takafumi; Kozuki, Seiya et al. Film thermoelectric generator of multiple 2-D electron gas. IEEE Transactions on Electron Devices. 2024, 71, 4834. doi: 10.1109/TED.2024.3412863
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