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Negative-Differential-Conductance RTD Amplifier MMIC With Record FOMs of Gain-to-DC Power Ratio and Noise Figure

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***Short-Abstract*—An ultralow-dc-power negative-differential-conductance (NDC) microwave amplifier using resonant tunneling diodes (RTDs) is presented and its noise figure characteristic is for the first time reported. The fabricated amplifier exhibits an extremely low dc-power consumption of 155 μW along with good RF performances of an RF gain of 8.1 dB, a return loss of more than 11 dB, and a noise figure of 4.5 dB at 5.5 GHz. The gain-to-dc power ratio was estimated to be 52.2 dB/mW. The figures-of-merit (FOMs) of the achieved gain-to-dc power ratio and noise figure are record for sub-mW low-power monolithic amplifiers at the related frequency band.**

I. INTRODUCTION

The InP-based resonant tunneling diodes (RTDs) can be employed in the low-power microwave amplifier for short range wireless sensor systems because of their excellent negative differential conductance (NDC) characteristic obtained at extremely low DC power [1]-[3]. In the previous works, we have reported the preliminary results of the sub-mW RTD-based amplifier at 5 GHz [2] and recently obtained ultralow-dc-power RTD gain characteristics at a frequency of 5.7 GHz [3]. In order to employ the low-power RTD-based amplifier in the practical wireless sensor systems as a low noise amplifier, a low noise figure characteristic is highly required. The RTD is expected to be a promising electron device for the low-noise microwave amplifiers due to the intrinsic quantum resonant tunneling phenomena observed at an extremely low bias current [4].

In this work, we report on an RTD-based microwave amplifier with record figures-of-merit (FOMs) of gain-to-dc power ratio and noise figure characteristics. The RTD amplifier has been implemented by using an InP-based MMIC (monolithic microwave integrated circuit) technology.

II. AMPLIFIER DESIGN AND DEVICE TECHNOLOGY

Fig. 1 shows the circuit configuration of the RTD-based amplifier, which consists of two RTDs and a hybrid coupler [1]-[3]. The ideal voltage gain of the amplifier is represented as the magnitude of the reflection coefficient (Γ) given by $(Z_D\text{-}Z_O)/(Z_D+Z_O)$, where Z_O is the output characteristic impedance of the coupler and Z_D is the total impedance including a negative conductance (g_D) of the RTD [1]. The amplifier was designed such that the Z_O value approaches the

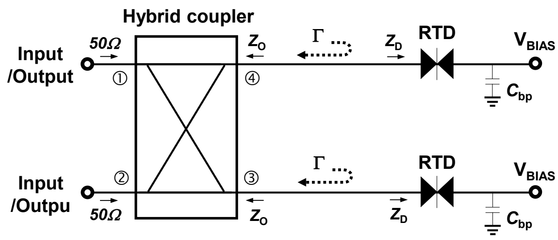
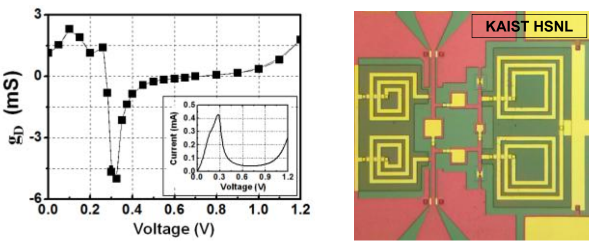


Fig.1. Schematic diagram of the RTD-based amplifier.



(a) (b)

Fig.2. (a) RF-modeled negative conductance (g_D) of the fabricated RTD with an emitter mesa area of 0.9 × 0.9 μm^2 (inset: the measured dc I-V characteristic of the RTD at room temperature) and (b) microphotograph of the fabricated RTD amplifier.

inverse of the g_D magnitude at the NDC bias voltage range, while satisfying its intrinsic stability criteria [5]. The bypass capacitor (C_{bp}) was integrated to eliminate a bias line effect of the NDC devices by forming an ac ground at the V_{BIAS} mode. To implement an ultralow-dc-power amplifier, the RTDs, spiral inductors, MIM capacitors, and thin-film resistors were integrated using an InP MMIC technology. The detailed layer structure and fabrication process have been described previously [2]. Fig. 2 (a) shows the RF modeled g_D characteristic of the fabricated RTD with an emitter mesa area of 0.9 × 0.9 μm^2. The inset exhibits the measured dc I-V characteristics of the RTD featuring a relatively high PVCR of 11.2 with a low I_P of 430 μA. The return loss and isolation of the hybrid coupler, which consists of four spiral inductors and four MIM capacitors with a Z_O of 250 Ω [2], were measured to be -13.7 dB and -16.4 dB at 5.5 GHz, respectively. The capacitance per area of the capacitors was measured to be 0.28

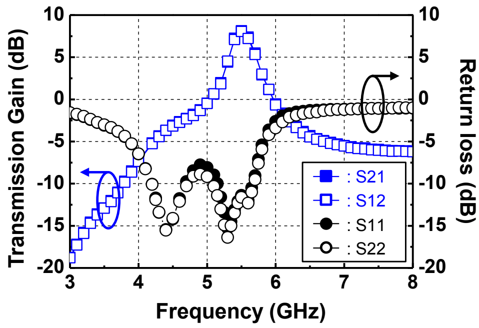


Fig.3. Measured transmission gain and return loss of the RTD-based amplifier.

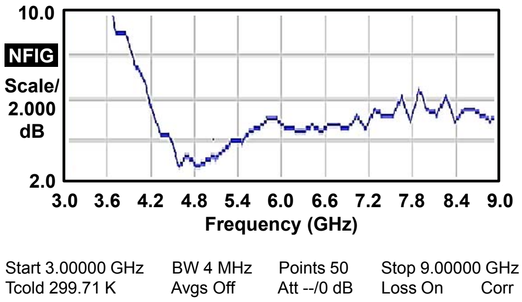


Fig.4. Measured noise figure of the RTD-based amplifier.

fF/μm^2. The inductance of the inductors was in a range of 0.81 - 1.43 nH for proper operation of the coupler.

III. Measurement And Discussion

Fig. 2 (b) shows the microphotograph of the fabricated amplifier with a chip area of 390×550 μm^2 excluding the pads. The S-parameter measurements of the fabricated IC were performed on wafer using an Anritsu 37000E network analyzer. Fig. 3 shows the measured transmission gain and return loss characteristics under bias conditions of V_{BIAS} = 0.33 V and I_{BIAS} = 235 μA with an ultralow-dc-power consumption of 155 μW. The maximum gains of S21 and S12 are measured to be 8.1 dB and 8.13 dB at 5.5 GHz, almost symmetric due to the inherent reciprocal properties. The return losses of S11 and S22 at the same frequency were measured to be -11.4 dB and -11.6 dB, respectively. In order to investigate the possibility as a low-noise amplifier for the practical ultralow-power receiver systems, the noise figure of the RTD-based NDC amplifier was for the first time characterized by using a noise figure analyzer (Agilent N8975A). Fig 4 shows the measured noise figure characteristic of the amplifier in the frequency band of 3 to 9 GHz. The noise figure is measured to be less than 5 dB over the frequency range of 4.3 to 7 GHz, exhibiting a value of 4.5 dB at the maximum gain frequency of 5.5 GHz. The achieved noise figure is caused by the noise of the RTD devices and the losses of the hybrid coupler used in the NDC amplifier. The series resistance and differential resistance in the RTD devices and the parasitic resistances of the coupler are expected to be main noise contributors. The overall noise figure performance of the amplifier will be further investigated in detail.

TABLE I

Performance Comparison with Other Low-power Amplifier MMICs Operating at The 5 GHz Frequency Band.

	[6]	[7]	**This work**
Technology	90 nm CMOS	180 nm CMOS	**0.9 μm RTD**
f_0 (GHz)	5.1	5	**5.5**
Gain (dB)	10.3	10.23	**8.1**
Power Consumption (mW)	1.03	0.8	**0.155**
Noise Figure (dB)	5.3	4.1	**4.5**
Gain-to-dc power ratio (dB/mW)	10.2	12.8	**52.2**

Table I shows the performance comparison of the fabricated RTD-based amplifier with the other recently reported microwave low-power amplifiers for the 5 GHz frequency-band [6], [7]. Due to the achieved low dc-power consumption of 155 μW, the gain-to-dc power ratio of the RTD amplifier is estimated to be 52.2 dB/mW, which is about 4 times higher than that of the conventional amplifiers [6], [7]. The obtained noise figure of less than 5 dB is a good value, considering the relatively lower dc-power dissipation of the deep sub-mW range. The gain and noise figure characteristics are expected to be improved by further optimization of circuit design and device performance. The excellent FOMs of the gain-to-dc power ratio and noise figure characteristics show that the RTD technology is well suited for ultralow-dc-power microwave low noise amplifiers in the wireless sensor systems.

IV. Conclusion

An ultralow-dc-power RTD-based NDC microwave amplifier is presented and its noise figure characteristic is for the first time reported. The fabricated amplifier has shown record FOMs of the gain-to-dc-power ratio of 52.2 dB/mW and the noise figure of 4.5 dB under an extremely low dc-power consumption of 155 μW at 5.5 GHz. These results clearly show the feasibility of the RTD-based microwave amplifier for extremely low-power receiver systems.

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