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RF-to-DC Direct Power Conversion of AlGaAs/GaAs Schottky Diode for On-Chip Rectenna Device Application in Nanosystems

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Abstract: The Schottky diodes enjoined with coplanar waveguides are investigated for applications in on-chip rectenna device application without insertion of a matching circuit. The design, fabrication, DC characteristics and RF-to-DC conversion of the AlGaAs/GaAs HEMT Schottky diode is presented. The RF signals are well converted by the fabricated Schottky diodes with cut-off frequency up to 25 GHz estimated in direct injection experiments. The mW output power can be achieved by optimizing the material structure and ohmic metals so that lower series resistance is realized. Proper circuitry also should lead to maximum power conversion, for example the ground lines of the system are connected to the same point. Direct integration of the planar dipole antenna to the Schottky diode via coplanar waveguide transmission line may allow omission of any matching impedance circuit. The outcomes of these results provide conduit for breakthrough designs for ultra-low power on-chip rectenna device technology to be integrated in nanosystems.

Key words: Rectenna, coplanar waveguide, AlGaAs/GaAs, HEMT, Schottky diode, nanosystem

INTRODUCTION

Recent revolutionary progress of the internet and wireless technologies has created a concept of the ubiquitous network society for the new century. Evolution of all these technologies is producing new off-roadmap trends for semiconductor device research in addition to the main-stream Si CMOS technology. The new device trends include trends toward the quantum nanotechnology, toward use of new materials, toward realization of new functions sensors and actuators and use of new system architectures and toward formation of new wireless networks.

Recently, the concept of Intelligent Quantum (IQ) chip introduced by Hasegawa (2003) using III-V material as a base material where nanometer scale quantum processors and memories are integrated on chip with capabilities of wireless power supply, wireless communication circuit and various sensing functions, has been demonstrated. III-V materials are the most promising for high-frequency devices because of the high electron mobility and other unique features such as the formation of two-dimensional electron gas (2DEG). The devices switch faster as collisions are less frequent. Rectenna (combination of a rectifying circuit and an antenna) is one of the most promising devices to be integrated on the IQ chip to form the wireless power supply. This device can capture microwave power and convert to the DC power to generate the other on-chip nanoelectronic devices or circuits. Schottky diodes are known for their fast rectifying features and hence are ideal for applications as rectenna (Sharma, 1984).

Almost all past rectennas were designed using various material for over 100 mW rectifying and the RF-DC power conversion efficiency is less than 20% at the 1 mW microwave input (Suh and Chang, 2002). However, the design and fabrication of ultra-low power n-AlGaAs/GaAs high-electron-mobility-transistor (HEMT) Schottky diode for on-chip rectenna does not appear in the published literature. As a by-product of our group's investigations (Hashim *et al*., 2007a, b, 2008), THz wave detectors, plasma-wave THz amplifiers, RF power detectors utilizing the same AlGaAs/GaAs HEMT structure and several other unique features have been reported.

In this study, we present the possible direct integration of Schottky diode to planar dipole antenna via coplanar waveguide (CPW) without insertion of any matching circuit. The design and fabrication of Schottky diode is directed towards fast conversion of RF signals in

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nanocircuits and nanosystems to supply ultra low DC power. The DC and RF characterizations of Schottky diodes are presented.

POSSIBLE DIRECT INTEGRATION OF SCHOTTKY DIODE WITH DIPOLE ANTENNA

The possible direct connection between Schottky diode and planar dipole antenna is illustrated in Fig. 1. This proposed configuration is designed on the same substrate with components directly connected to each other. This is purposely done to model, characterize and observe the simultaneous behavior of the Schottky diode and planar dipole antenna around the operating frequency.

A planar integrated fabrication of this nature can guarantee excellent mechanical tolerances for a wide variety of tuning features. The results show excellent usefulness of the proposed Schottky diode configuration and the effectiveness of uniplanar technology with high performance-to-cost ratio. Next section will present the

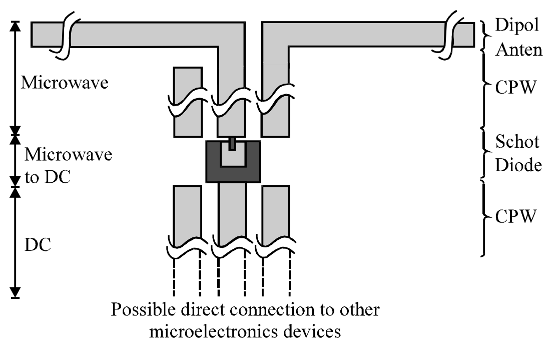

Fig. 1: Schematic of direct integration between Schottky diode and dipole antenna

details of Schottky diode's design and characterization. However, the design and characterization of a dipole antenna are presented elsewhere (Mustafa *et al*., 2010).

DESIGN AND FABRICATION OF SCHOTTKY DIODE

Schottky diode was fabricated on the AlGaAs/GaAs layered structure grown by molecular beam epitaxy. The higher electron mobility in 2DEG layer exists because of modulation doping in which the scattering by impurities is considerably suppressed. AlGaAs/GaAs heterostructures confine electrons so itinerant electron motion is confined in two dimensions only. It has emerged to be suitable nanostructure for the development of the so-called IQ chip which has been considered as the most promising chip structure for future ubiquitous network society (Hasegawa, 2003). The characteristics of the layered nanostructure are as follows: 625 μm semi-insulated GaAs substrate with 500 nm GaAs buffer layer on top; 10 nm AlGaAs buffer (spacer) layer; 20 nm undoped GaAs layer; 10 nm AlGaAs spacer layer; n-doped AlGaAs (Si δ doping) barrier layer; terminated with 10 nm GaAs undoped cap layer. The devices were designed and fabricated using photolithography and a standard lift-off technique. The carrier mobility and the carrier sheet density obtained by Hall measurements at room temperature were 6040 $cm^2/Vsec$ and 8.34×10^{11} cm^{-2}, respectively.

The Schottky electrode was formed by Ni/Au and ohmic electrode was formed by alloyed Ge/Au/Ni/Au. As shown in Fig. 2a, the fabricated device has a CPW configuration at both sides of Schottky and ohmic contacts possessing GSG pad structure. The dimension of the gap a and width b for CPW obtained from Wheeler's

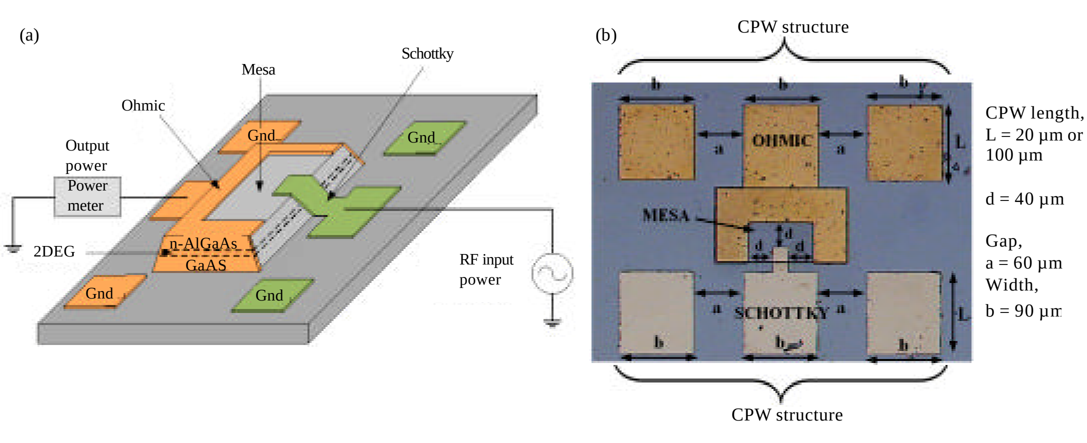

Fig. 2: (a) Schematic and (b) fabricated Schottky diode (top view)

equation (Wen, 1969) were chosen to be 60 and 90 μm, respectively in order to produce the characteristic impedance Z_0 = 50 Ω. The Schottky contact area, A is 20x20 μm. The length of CPWs is 100 μm. The distance d between Schottky-ohmic contacts is 40 μm. The fabricated Schottky diode is shown in Fig. 2b. The choice is compatible with the antenna characteristics without insertion of matching circuit. This CPW structure permits direct injection of RF signal through Cascade GSG Infinity-150 microprober.

MEASURED RESULT OF SCHOTTKY DIODE AND DISCUSSION

Current-voltage (I-V) measurement: After fabricating the Schottky diode, the DC I-V characteristics were measured using Keithley semiconductor characterization system Model 4200 and micromanipulator probe station. As shown in Fig. 3, the DC I-V curve of fabricated Schottky diode shows a diode I-V curve with series resistance, R_{series} of 909.1 Ω. The series resistance is defined as the inverse slope between 2.0 V and 3.0 V. The threshold voltage, V_{TH}, for the devices is estimated to be 1.1 V as shown in Fig. 3 inset.

The Schottky barrier height (SBH), ϕ_B of the device is extracted from the reverse saturation current, I_s given by the Richardson-Dushman equation for the thermionic emission (Sharma, 1984):

$$\phi_B = V_t \cdot \ln\left(\frac{A \cdot A^* \cdot T^2}{I_S}\right) \quad (1)$$

where, V_t is the thermal voltage, A* is the effective Richardson constant, A is the area of the metal-semiconductor contact and T is the absolute temperature. The reverse leakage current is 3.97 nA and extracted ϕ_B is found to be 0.5289 eV. The SBH value is almost three times smaller than the ideal value of 1.443 eV. This decrease in the barrier height is attributed to the smaller contact area as this parameter is included in Eq. 1, consistent with Jeon *et al.* (2004). The reduction of the Schottky barrier height is also due to the fabrication process, i.e. the annealing process, which can result in a decrease in barrier height as suggested by Zhang (1999). They have reported Schottky contacts of different metals to n-type AlGaAs/GaAs structures and proposed a model which involves the quality of the contact and defect formation at the semiconductor surface due to

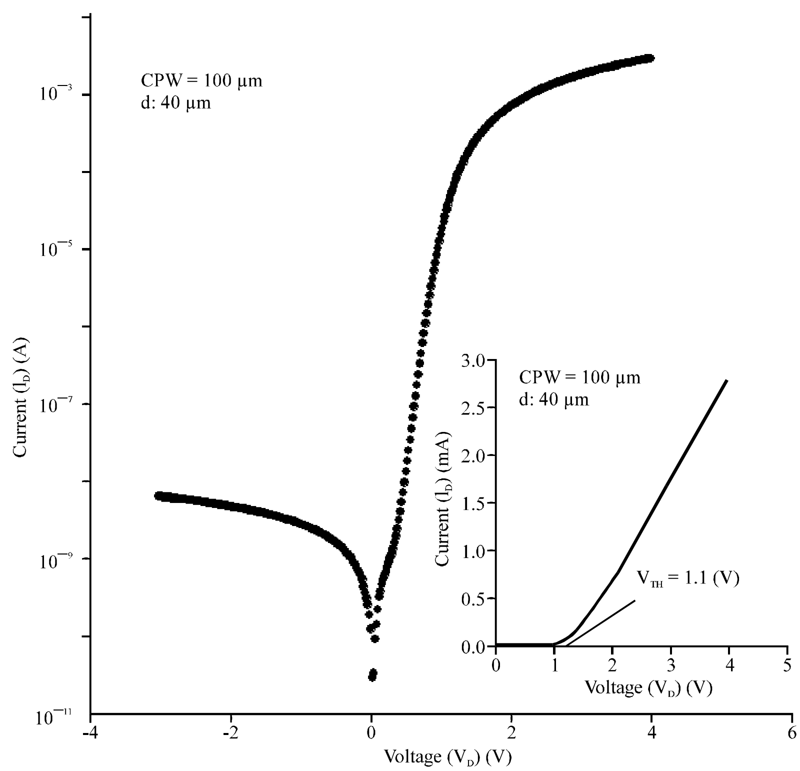

Fig. 3: DC I-V characteristics of fabricated Schottky diode

interdiffusion and/or penetration of metal into semiconductor. This model can qualitatively explain the difference in barrier heights and degradation of the barrier due to a certain process. In addition, this was also reported by Milanovic *et al.* (1996), where the work functions of the metal and the semiconductor are determined by the process. The actual nature of the metal-semiconductor contact is not controllable and in fact may vary substantially from one process to another. This reduced barrier height is beneficial for improved RF response and rectification as it requires a lower turn-on voltage (Jeon *et al*., 2004).

RF-DC conversion measurement: To achieve a high cut-off frequency, the rectifying metal-to-semiconductor contact area must be reduced. However, too small a contact area limits the delivery of the maximum power before the diode burns out. Therefore, the area of the diode A is the major design parameter since most of the other parameters such as the work function of the metal and the semiconductor are determined by the fabrication process and interface properties. A simple measurement setup, as shown in Fig. 2a, was assembled.

Figure 4 shows the rectified output power as a function of frequency at an input power level of 5, 15 and 18 dBm. The maximum output power is achieve around 5 to 10 GHz at input power level of 18 dBm. The input power is limited to 18 dBm due to the equipment capability. It can be seen that, the output power decrease to low value at high frequency. The cut-off frequency for this device is estimated to be around 25 GHz. Figure 5a and b show the rectified output power as a function of input power in dBm and mW, respectively. A quadratic rise of output power as a function of input power as a result of power sweep from -10 dBm to 25 dBm at 1, 10, 15 and 25 GHz can be seen in Fig. 5a. The output power starts to rise at the input power level of 5 to 18 dBm for all tested frequencies where at this level, the input voltage is confirmed at the same level with the turn-on voltage of a diode. Figure 5b also shows that the maximum output power is obtainable at certain frequency. In this measurement, the device seems to show a maximum power at 10 GHz. Such characteristics also suggest a potential application as a frequency-tunable rectenna device.

As indicated in previous section, the study on ultra-low power n-AlGaAs/GaAs HEMT Schottky diode for on-chip rectenna does not appear in the published

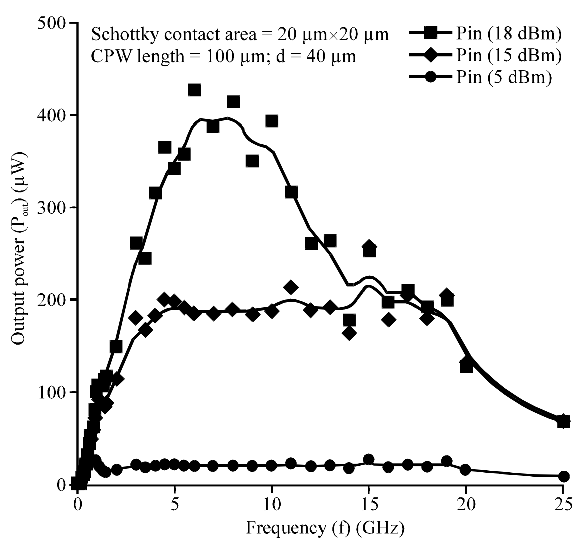

Fig. 4: Rectified output power as a function of frequency

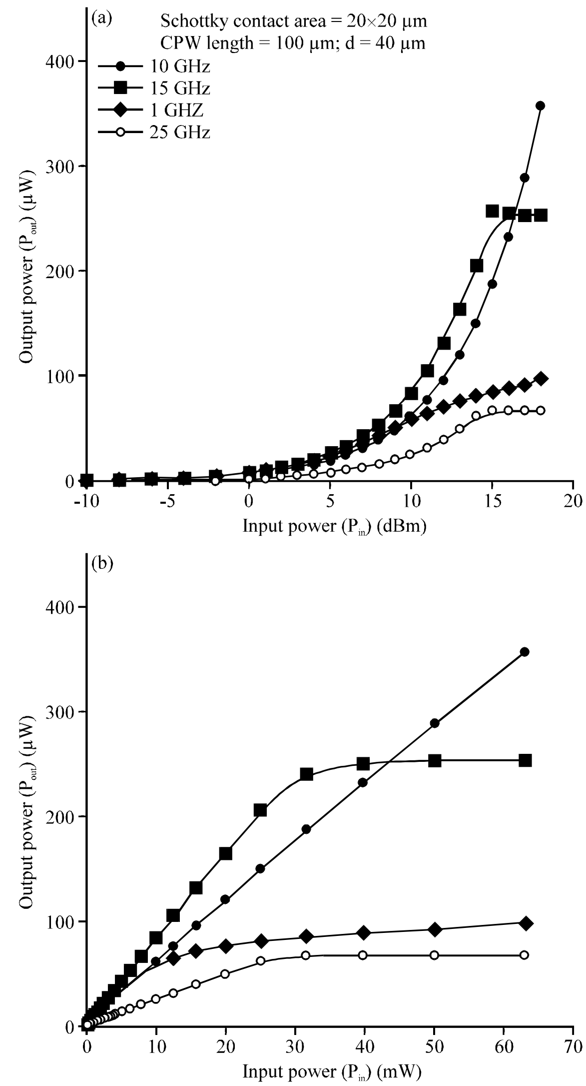

Fig. 5: Rectified output power as a function of injection power in (a) dBm and (b) mW

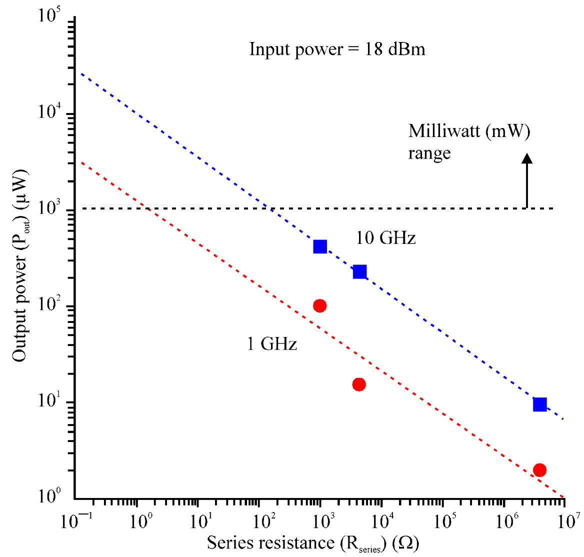

Fig. 6: Rectified output power as a function of series resistance

literature. To project ultra-low power rectenna for operation in milliwatt (mW) range, the RF-to-DC power conversion of Schottky diode has also been measured for the other samples which are fabricated on the same wafer and have same values of turn-on voltages but different dc series resistance, R_{series}. Figure 6 shows the rectified output power as a function of series resistance of devices at input power of 18 dBm. A linear characteristics of output power as a function of series resistance for 1 and 10 GHz can be projected in Fig. 6. It can be assumed that the output power will shift towards milliwatt range with the decreasing of device series resistance. The reduction series resistance can be achieved by removing cap layer and forming ohmic contact directly on the n-AlGaAs/GaAs barrier layer. The rectifying response also can be improved by lowering the SBH. In this study, RF-DC power conversion efficiency is not calculated. This is because of the actual reflected and transmitted signal is not determined due to a constraint in equipment availability. The determination of power conversion efficiency will be carried out in the next work. The improvement of material and device structure should improve the power conversion efficiency. The proper measurement circuitry should also permit maximum power conversion. We believe that if the ground lines of the system are connected to the same point, maximum power conversion can be extracted.

CONCLUSION

The Schottky diode on AlGaAs/GaAs HEMT structure has been analyzed for on-chip rectenna device application. The cut-off frequencies of the fabricated Schottky diodes have been shown to be around 25 GHz estimated in direct injection experiments. The mW output power can be achieved by optimizing the material and ohmic metals so that lower series resistance is produced. The feasibility for direct integration of the planar dipole antenna to the Schottky diode without matching impedance circuit has been demonstrated. These results will provide new breakthrough ideas for the direct on-chip integration technology towards realization of ultra-low power on-chip rectenna technology to be integrated in nanosystems.

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