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Fabrication and Characterization of n-AlGaAs/GaAs Schottky Diode for Rectenna Device Application

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Abstract Schottky diode was designed and fabricated on n-AlGaAs/GaAs high electron mobility transistor (HEMT) structure for rectenna device application. Rectenna is one of the most potential devices to form the wireless power supply which is really good at converting microwaves to DC. The processing steps used in the fabrication of Schottky diode were the conventional steps used in standard GaAs processing. Current-voltage (I-V) measurements showed that the device had rectifying properties with a barrier height of 0.5468 eV for Ni/Au metallization. The fabricated Schottky diode detected RF signals and the cut-off frequency up to 20 GHz was estimated in direct injection experiments. These preliminary results will provide a breakthrough for the direct integration with antenna towards realization of rectenna device application.

1. Introduction

The demanding modern commercial industry has stimulated research and development in wireless technology. Therefore, it has created a concept of wide spread “ubiquitous network society” for the new country. This technology is seen as a key in a development towards an increasingly digitized public space in which people and objects are connected through digital networks [1].

In this report, we elaborate on current research to introduce the Intelligent Quantum (IQ) chip introduced by Hasegawa et al. [2] which coincide to this ubiquitous concept with sizes of millimeter square or below. This IQ chip, consists of rectenna as a function of wireless power supply which can operate at lower voltages, that communicates and generate to other devices or circuits. A “rectenna” is a rectifying antenna. The main component of the rectifying circuit is the Schottky diode. Schottky diode based on n-AlGaAs/GaAs HEMT structure was chosen due to its high performance in rectifying circuit that is widely used for new wireless technology. An antenna received the electromagnetic power and Schottky diode converts it to electric power.

The III-V materials allow much greater flexibility in band structure engineering and thereby device design for both high performance and low power applications [3]. Therefore, this portable devices of Schottky diode should have small dimensions and suitable for low power and millivolts rectenna application. This Schottky diode based HEMT structure is proposed because of the high electron mobility and other unique features such as the formation of two-dimensional electron gas (2DEG) layer [4].

The rectenna operating at 2.45 GHz has been studied extensively. For this report, we are focusing on designing, fabrication and characterization of Schottky diode towards rectenna device application. Higher frequency rectenna need to be developed which is to integrate with dipole antenna without any matching circuit as reported before [5]. The behavior of the antenna and Schottky diode has to be modeled at and around the operating frequency for low power rectenna [6] device applications. In this work, we have analyzed the performance of 10 MHz to 30 GHz Schottky diode for rectenna device application.

2. Design and Fabrication of Schottky Diode

We have chosen to build Schottky diode on AlGaAs/GaAs HEMT structure because of the higher electron mobility that can be provided by two-dimensional electron gas (2DEG) layer. HEMTs are promising devices for millimeter-wave due to their excellent high frequency and low-noise performance [7]. The carrier mobility and the carrier sheet density obtained by Hall measurements at room temperature were $6040 \text{ cm}^2/\text{V}\cdot\text{sec}$ and $8.34 \times 10^{11} \text{ cm}^{-2}$, respectively. The AlGaAs/GaAs modulation-doped heterostructure was grown by molecular beam epitaxy (MBE). Figure 1(a) shows the illustration of fabricated device structure and microscope image from the top view of the fabricated Schottky diode is shown in Figure 1(b). The devices are facilitated with a co-planar waveguide (CPW) structure, at the both sides, which possess ground-signal-ground pad structures and connected to a Schottky diode so that direct injection of RF signal can be performed. This CPW structure was designed to make the direct integration with antenna without any matching circuit inserted. The CPW structure permits direct injection of RF signal through Cascade ground-signal-ground (GSG) Infinity-150 microprober. In this preliminary study, the Schottky contact area, A is $20 \mu\text{m} \times 20 \mu\text{m}$, the lengths of CPW, L is $20 \mu\text{m}$ and the distances between Schottky-ohmic contacts, d is $40 \mu\text{m}$.

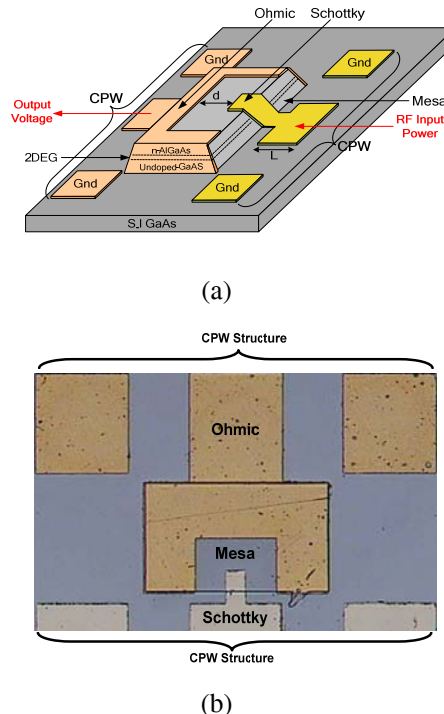


Figure 1. (a) Illustration of fabricated device structure and (b) Microscope image of Schottky diode

The devices were patterned and fabricated using photolithography and a standard lift-off technique. The processing steps used in the fabrication were the conventional steps used in a standard GaAs processing.

After the mesa was performed by wet chemical etching, the ohmic and Schottky electrode were formed by alloying Ge/Au/Ni/Au and Ni/Au, respectively. Annealing of the ohmic contacts was done by the rapid thermal annealing (RTA) method at 430°C for 5 minutes with N₂ flow. The metals were deposited at a pressure of 5×10^{-6} Torr by e-beam vacuum evaporator.

3. Schottky diode Measured Results

a) DC 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. Figure 2 below shows the DC measurement setup.

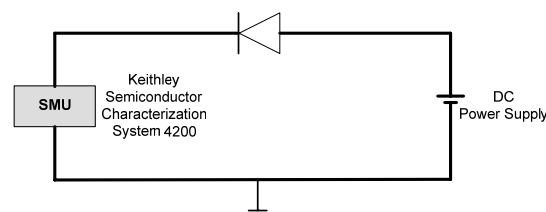


Figure 2. DC measurement setup

As shown in Figure 3 (inset), the DC I-V curve of a fabricated Schottky diode shows a diode I-V curve with a 1.176 kΩ series resistance, defined as the slope between 2 and 3 V. The threshold voltage, V_{th} was estimated to be 1.1 V.

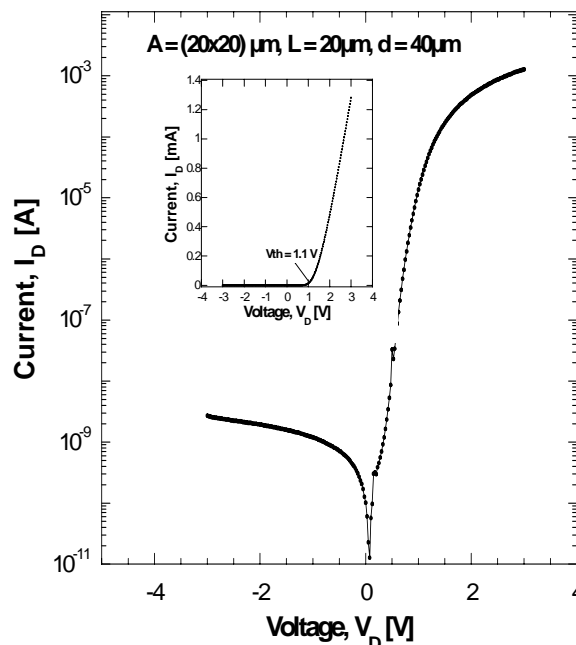


Figure 3. DC I-V curve for fabricated Schottky diode

As shown in Figure 3, can be estimated reverse saturation current, was 1.99 nA. The reverse saturation current of the device is used to calculate the Schottky barrier heights from the equation (1). Here, Φ_b is the barrier height in eV, I_s is the reverse saturation current, A^* is the effective Richardson constant, A is the area of the metal-semiconductor contact, and T is the absolute temperature. The

calculated Schottky barrier height is 0.5468 eV. This experimental barrier height is lower than the ideal calculated value, 1.443 eV. Based on the previous paper [8], to improve the RF response, the barrier height should be reduced because smaller barrier height gives better RF rectification due to lower turn on voltage.

$$I_s = AA * T^2 \exp\left(\frac{-q\phi_b}{kT}\right) \quad (1)$$

b) RF Measurement

The RF power detecting characteristics of the Schottky diodes, which has a $20 \mu\text{m} \times 20 \mu\text{m}$ contact area, were measured by directly injecting RF power through the GSG CPW structure using Cascade Infinity-150 microprober. We assembled a simple measurement setup as shown in Figure 4.

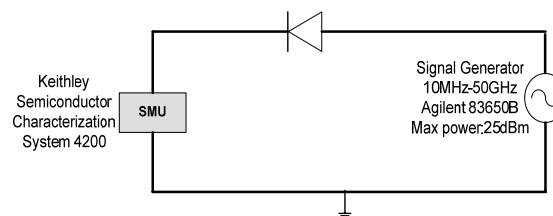


Figure 4. RF measurement setup

Figure 5 shows the rectified output voltages as a function of frequency at an input power level of 5 dBm, 15 dBm and 20 dBm and the cut-off frequency can be seen are 1 GHz, 7 GHz and 15 GHz, respectively. For the 20 dBm, the cut-off frequency at each tested input power level shows higher cut-off frequency than other input power.

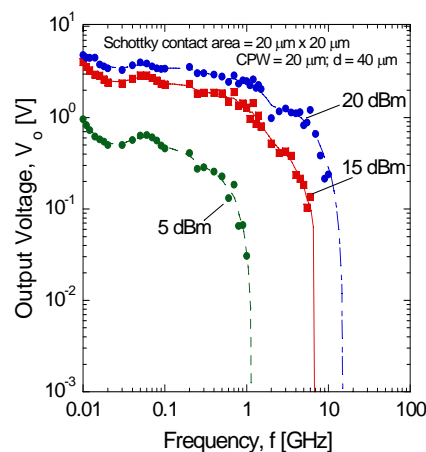


Figure 5. Rectified output voltage as a function of frequency

Figure 6 shows the rectified output voltage as a function of input power. As a glance, the measured result of a power sweep from -10 dBm to 25 dBm at 15 MHz, 1 GHz and 10 GHz shows a quadratic relationship between input power and detected voltage as expected. It can also be clearly seen that the output voltage starts to saturate at the input power level of 18 dBm. Therefore, the maximum cut-off frequency can be estimated at this power level. The cut-off frequency can be seen in those tested power range of 10 MHz to 30 GHz.

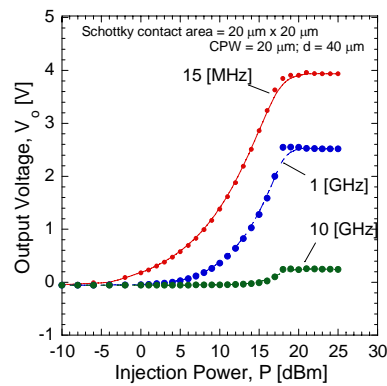


Figure 6. Rectified output voltage as a function of injection power

From Figure 6, we can translate those results obtained into Figure 7 where we can estimate the maximum cut-off frequencies. Here, we can assume a Schottky diode obeys the same expressions as a pn junction diode. The junction capacitance, C_j is proportional to contact area, A and the series resistance includes contact resistance is proportional to $1/\sqrt{A}$. Since the cut-off frequency is proportional to $1/R_s C_j$, then we can conclude that the cut-off frequency is proportional to $1/\sqrt{A}$ [8]. Therefore, to achieve higher cut-off frequency, the Schottky contact area need to be reduced. From Figure 7, the estimated maximum cut-off frequency for this Schottky diode is 20 GHz.

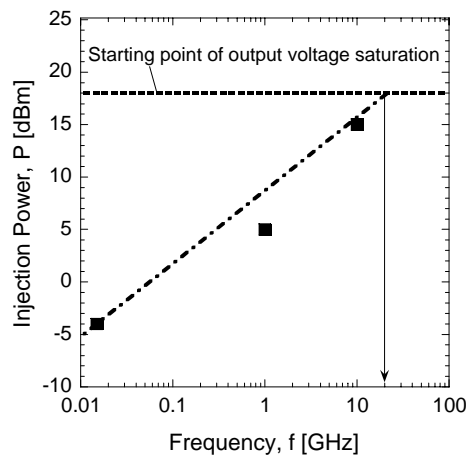


Figure 7. Minimum turn on power as a function of frequency

From the cut-off frequency equation;

$$f_c = \frac{1}{2\pi R_s C_j} \quad (2)$$

the junction capacitance, C_j was calculated to be 6.77 fF (with $R_s = 1.176 \text{ k}\Omega$ and $f_c = 20 \text{ GHz}$) which is larger than 2.014 fF (theoretical value).

We can expect that, the output voltage will decrease to millivolt (mV) if irradiation tests performed. Therefore, our proposed rectenna is suitable as a power supply to generate other devices operating at a lower voltage.

4. Conclusion

In this paper, the preliminary investigation on design, fabrication and characterization of the Schottky diode was performed. Direct RF injection was applied to the Schottky diode and high cut-off frequency up to 20 GHz was estimated. Therefore, the fabricated Schottky diode can contribute to the development of rectenna device operating in the frequency range of 10 MHz to 30 GHz. Based on the characteristics of the Schottky diode obtained from this study, it is expected that direct integration with the dipole antenna via CPW transmission line can be achieved without insertion of any matching circuit and thus, permit microwave irradiation. The output voltage of rectenna with microwave irradiation is expected to decrease from V to mV order [8]. However, such low voltage is expected to be sufficient for quantum nanodevice-based circuits which operate at ultra low power [9].

Acknowledgements

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