World Applied Sciences Journal 9 (Special Issue of Nanotechnology): 43-51, 2010
ISSN 1818-4952

Prediction of n-AlGaAs/GaAs Schottky Diode Properties for Milliwatt Range Application

[1]Norfarariyanti Parimon, [1]Farahiyah Mustafa, [1]Abdul Manaf Hashim,
[1]Shaharin Fadzli Abd Rahman, [1]Abdul Rahim Abdul Rahman,
[2]Mohd Nizam Osman, [3]Azlan Abdul Aziz and [3]Md. Roslan Hashim

[1]Material Innovations and Nanoelectronics Research Group,
Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
[2]Telekom Research & Development, TM Innovation Centre, 63000 Cyberjaya, Selangor, Malaysia
[3]Nano-Optoelectronics Research, Faculty of Physics,
Universiti Sains Malaysia, 11800 Minden, Penang, Malaysia

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 20 GHz estimated in direct injection experiments. Preliminary investigation on design, fabrication and DC and RF characteristics of the integrated device (planar dipole antenna + Schottky diode) on AlGaAs/GaAs HEMT structure is also presented. From the preliminary direct irradiation experiments using the integrated device, the Schottky diode is not turned on due to weak reception of RF signal by dipole antenna. Further extensive considerations on the polarization of irradiation etc. need to be carried out in order to improve the signal reception. 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 *et al.* [1] 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 [2] and hence are ideal for applications as rectenna.

Corresponding Author: Abdul Manaf Hashim, Material Innovations and Nanoelectronics Research Group, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
Tel: +607-5536230, Fax: +607-5566272, E-mail: manaf@fke.utm.my

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 [3]. 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 [4-6], 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 paper, 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 nanocircuits and nanosystems to supply ultra low DC power.

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 [1]. 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 $\text{cm}^2/\text{V-sec}$ and $8.34 \times 10^{11}\ \text{cm}^{-2}$, respectively.

The Schottky electrode was formed by Ni/Au and ohmic electrode was formed by alloyed Ge/Au/Ni/Au. As shown in Figure 1(a), 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 equation [7] were chosen to be 60 μm and 90 μm, respectively in order to produce the characteristic impedance Z_o = 50 Ω. The Schottky contact area, A is 20 μm x 20 μm. The length of CPWs is 100 μm. The distance d_{diode} between Schottky-ohmic contacts is 40 μm. The fabricated Schottky diode is shown in Figure 1(b). 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 Figure 2, the DC I-V curve of fabricated Schottky diode shows a diode I-V curve with series resistance 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 Figure 2 (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 [2].

$$I_s = AA^*T^2 \exp\left(\frac{\phi_b}{vV_t}\right) \tag{1}$$

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, consistent with [8]. This reduced barrier height is beneficial for improved RF response and rectification as it requires a lower turn-on voltage [8].

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 detection capability 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

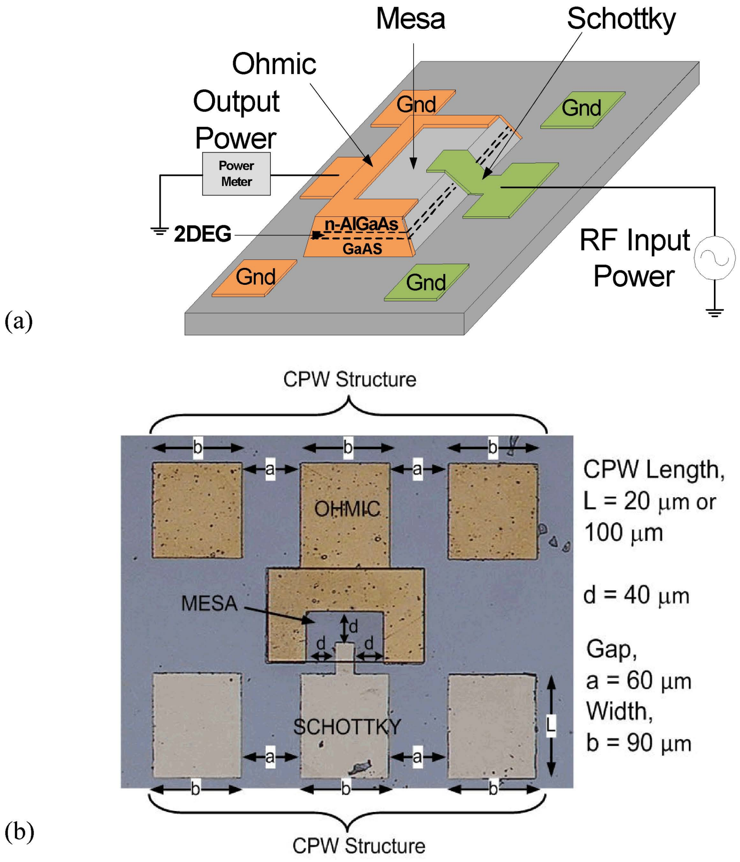


Fig. 1: (a) Schematic and (b) fabricated Schottky diode (top view)

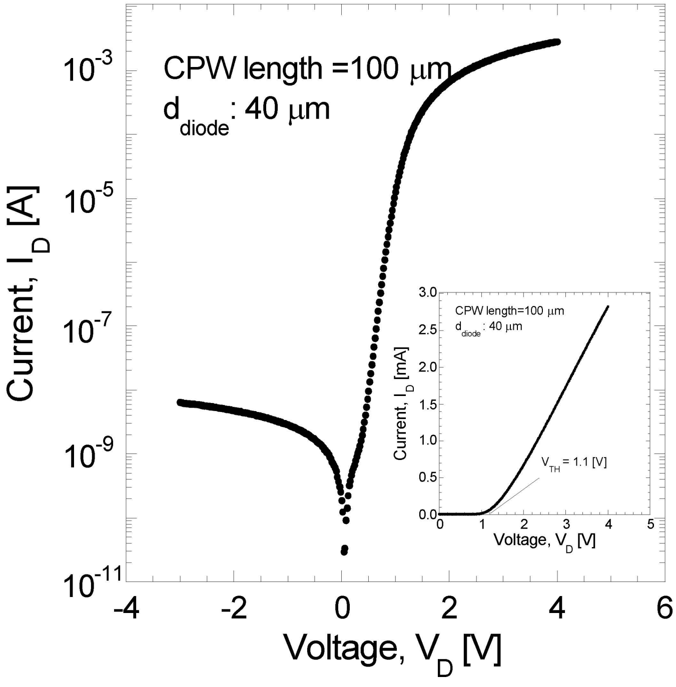


Fig. 2: DC I-V characteristics of fabricated Schottky diode

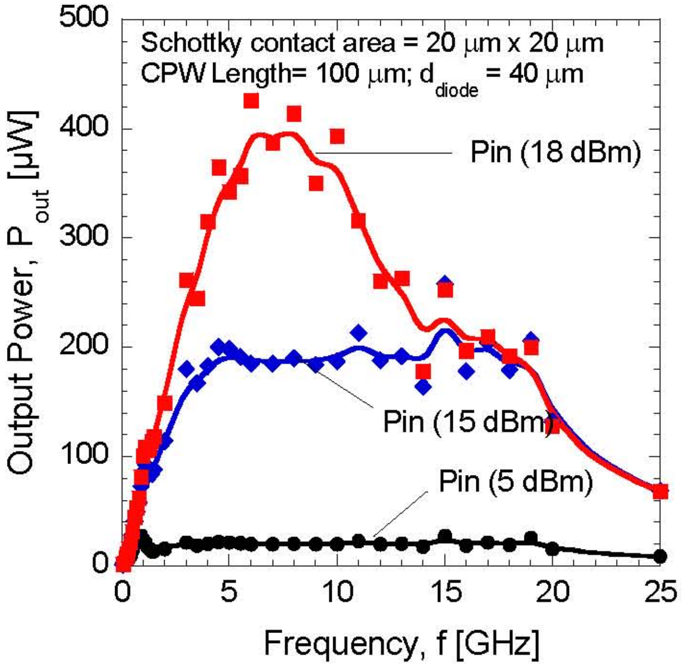


Fig. 3: Rectified output power as a function of frequency

determined by the fabrication process and interface properties. A simple measurement setup, as shown in Figure 1a, was assembled.

Figure 3 shows the rectified output power as a function of frequency at an input power level of 5 dBm, 15 dBm and 20 dBm. The maximum output power is achieve around 5 GHz to 10 GHz at input power level of 20 dBm. 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 20 GHz. Figure 4(a) 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 GHz, 10 GHz, 15 GHz and 25 GHz can be seen in Figure 4. The output power starts to saturate at the input power level of 15 dBm to 18 dBm for all tested frequencies.

As indicated in Sec I, the study on ultra-low power n-AlGaAs/GaAs HEMT Schottky diode for on-chip rectenna does not appear in the published literature. To project ultra-low power rectenna, the RF-to-DC power conversion of Schottky diode has also been measured for the other samples and plotted in Figure 5. Figure 5 shows the rectified output power as a function of series resistance, R_{series} of devices. A linear characteristics of output power as a function of series resistance for 1 GHz and 10 GHz can be projected in Figure 5. It can be assumed that the output power will shift towards milliwatt (mW) range with the decreasing of device series resistance. The reduction series resistance can be achieved by reducing the Schottky contact area. The rectifying response also can be improved by lowering the SBH. The improvement of measurement technique and device structure also can improve the conversion efficiency.

Integration of Schottky Diode and Dipole Antenna: The possible direct connection between Schottky diode and planar dipole antenna is illustrated in Figure 6(a). Based on the design and obtained results of the dipole antenna [9] and Schottky diode presented before, it is expected that direct integration via short CPW transmission line between Schottky diode and dipole antenna can be achieved without any matching circuit. 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.

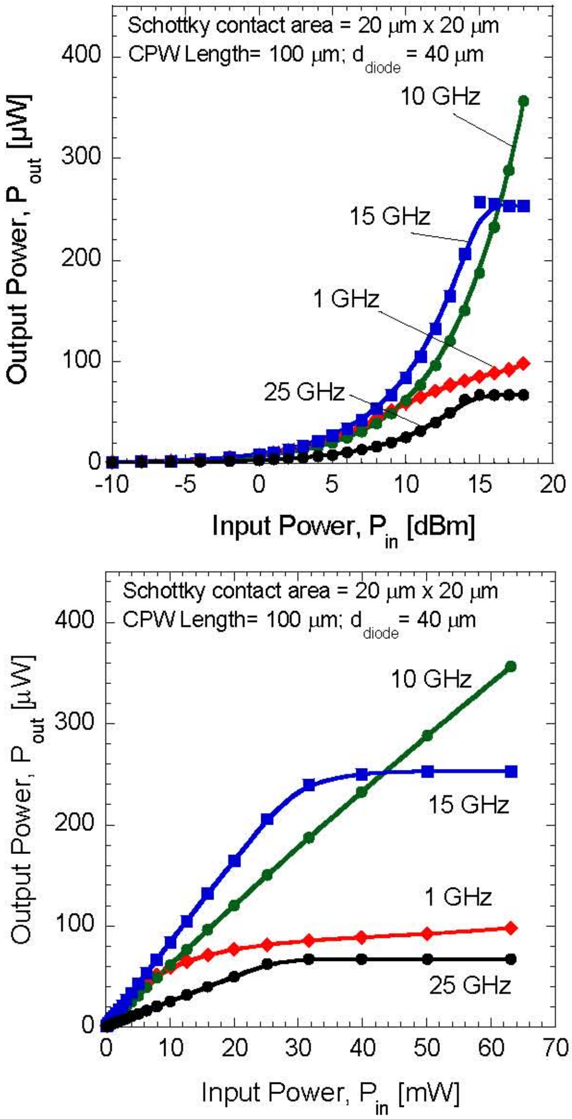


Fig. 4: Rectified output power as a function of injection power in (a) dBm and (b) mW

The integrated dipole antenna and Schottky diode device without insertion of matching circuit as illustrated in Figure 6(a) is fabricated using standard photolithography and lift-off process. Figure 6(b) shows the fabricated on-chip integrated dipole antenna and Schottky diode. The lengths of dipole antenna have been chosen to be 3 mm and 6 mm with width of 100 μm and metal thickness of 50/50 nm of Cr/Au. As presented in [9], the width and metal thickness of dipole antenna have only an effect on the magnitude of return loss but does not give any effect on the resonant frequency and bandwidth. The on-chip integration is expected to generate at SHF range which is 3 to 30 GHz.

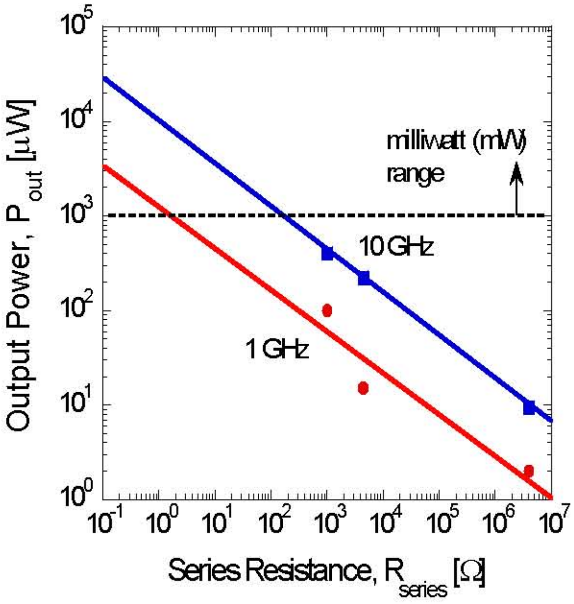


Fig. 5: Rectified output power as a function of series resistance

DC I-V and RF-DC Conversion Characteristics: In this section, we investigated the diode characteristics in order to confirm the potential of the fabricated devices. Figure 7 shows the DC *I-V* curve of the Schottky diode with series resistance of 9.22 kΩ defined at slope between 2 and 3 V. The threshold voltage is estimated to be 1.7 V as shown in Figure 7 (inset). The reverse leakage current for the fabricated devices is 399 nA and SBH was calculated to be 0.4095 eV.

The RF-DC conversion characteristics of Schottky diode was investigated using oscilloscope connected at the output side as shown in Figure 8. Figure 9 shows the average rectified voltages, $V_{out(peak)}$ as a function of input voltages at different frequency level of 10 MHz, 50 MHz and 100 MHz. In the direct injection experiment with load of 1 MΩ, it can be seen that the rectified output voltages are only obtainable when the input voltages exceed the turn-on voltage of diodes which is 1.7 V.

Direct RF Irradiation: An experimental set-up for the direct RF irradiation is shown in Figure 10. RF signal is irradiated to the sample through horn antenna. The distance, *d* of horn antennas and the devices is around 15 cm as shown in Figure 10. Spectrum analyzer is used to measure the reception of RF power before entering Schottky diode.

Figure 11(a) and (b) show the received power as a function of frequency for antenna length of 3 mm and 6 mm, respectively. It was confirmed that the resonant

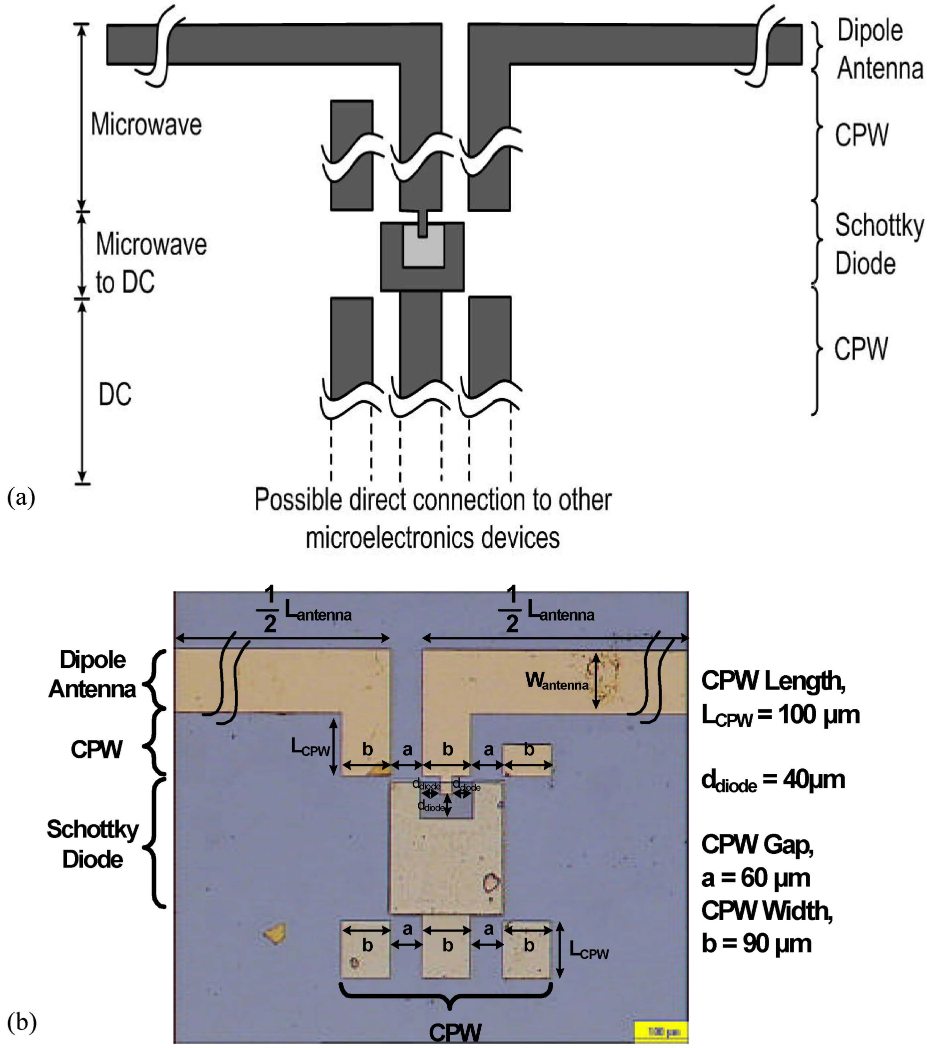


Fig. 6: (a) Schematic and (b) fabricated devices of direct integration between dipole antenna and Schottky diode

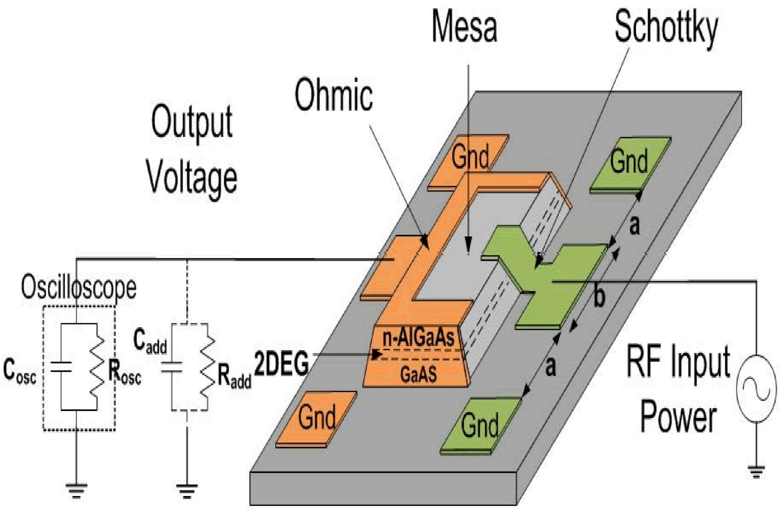


Fig. 7: Measurement setup for RF-DC conversion characteristics of fabricated devices

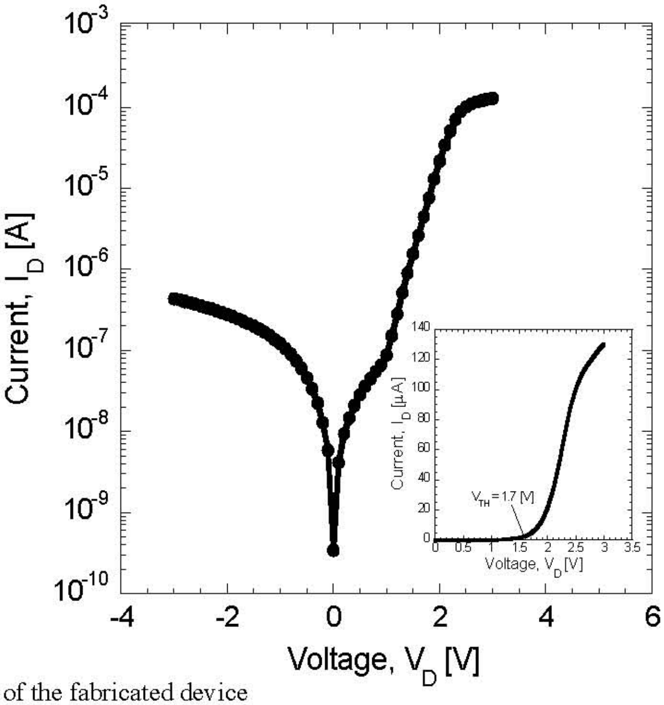


Fig. 8: DC *I-V* Curve of the fabricated device

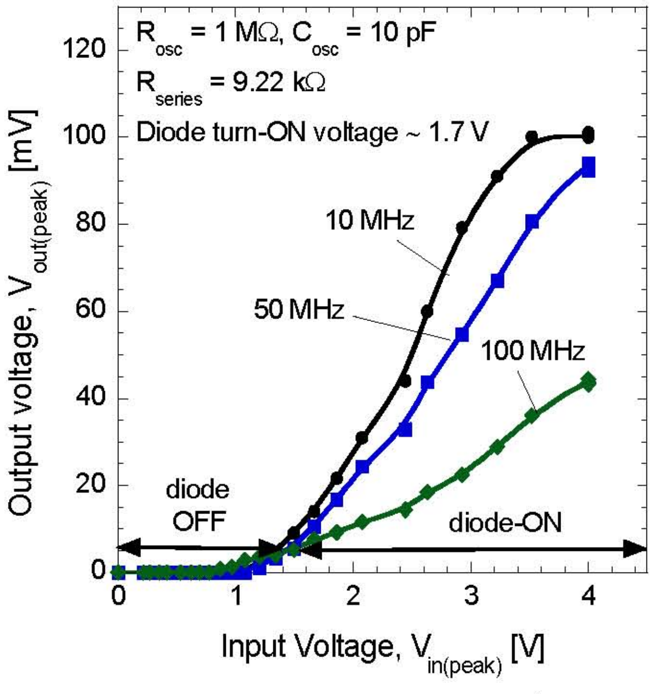


Fig. 9: Rectified output voltages as a function of input voltages for R_{osc} = 1 MÙ and C_{osc} = 10 pF at different frequency

frequency of antenna with length of 3 mm and 6 mm is 18.2 GHz and 8.2 GHz. Therefore, maximum power should be received by antenna at these frequencies. However, it can be seen that weak signal reception around -30 dBm was measured for both devices as shown in Figure 11(a) and (b).

This power level is not enough to turn on the diode since the power turning-on the diode is about 7 dBm which is equivalent to 1.7 V in the direct injection experiment. In this preliminary measurement, we do not consider the polarization of horn antenna and dipole antenna yet. Further consideration on the polarization,

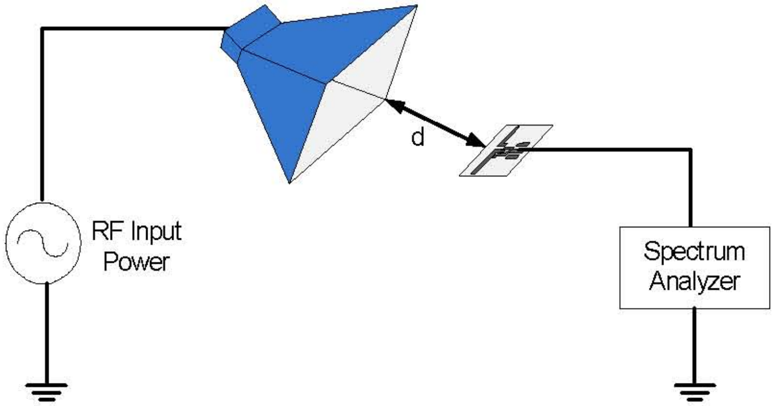
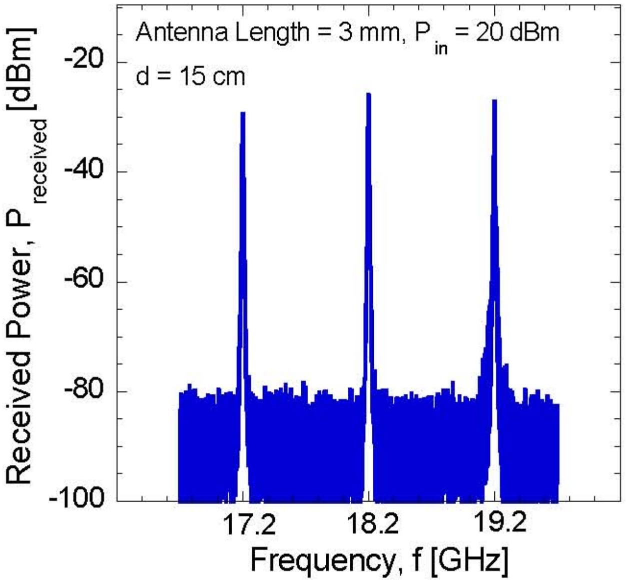
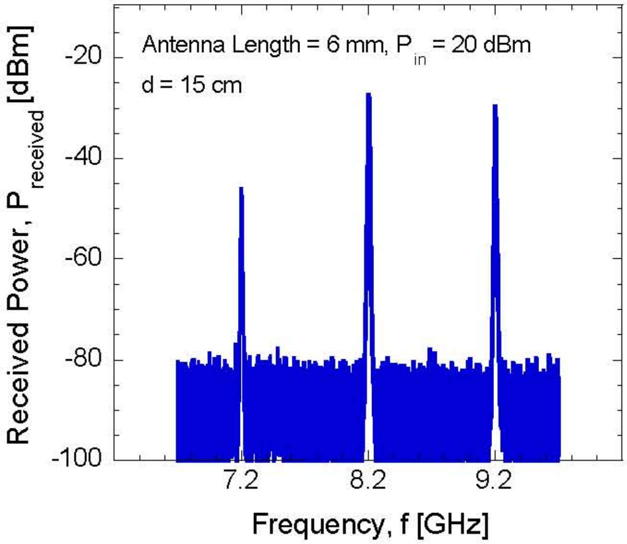


Fig. 10: Direct irradiation measurement setup



(a)



(b)

Fig. 11: Generated received power as a function of frequency for antenna length of (a) 3 mm and (b) 6 mm

balance and unbalance will be carried out so that optimum power can be received to turn on the Schottky diode.

In this paper, the dipole antenna is designed to work up to 18.0 GHz. However, the output signal of the diode is too weak to be detected when it is operated at such high frequency, as shown in Figure 11. When the dipole antenna is integrated with the diode, the output signal becomes weaker than that of diode.

There are three possible solutions that can be done in future in order to improve our preliminary results. First, the length of dipole antenna should be increase in order to reduce the resonance frequency of the dipole antenna. It noted that fundamental resonant frequency shifts to higher frequency when the length of antenna decreases. Another solution is the barrier height of diode should be reduced because smaller barrier height gives better RF rectification due to lower turn on voltage. The other is by considering the other type of planar antenna for receiving signal such as meander type. The preliminary results presented in this paper will provide a new breakthrough for the direct integration for real application.

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 adequate up to 20 GHz estimated in direct injection experiments. The mW output power can be achieved by reducing Schottky contact area in order to get lower series resistance. The preliminary investigation on design, fabrication and RF characterization of the integrated devices was introduced. From the preliminary direct irradiation experiments, the Schottky diode is not turned on due to weak reception of RF signal by dipole antenna. Further considerations on the polarization of irradiation etc. need to be carried out to improve the signal reception. Furthermore, optimization on the device structures and measurement techniques should also improve the power conversion for on-chip application. 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.

ACKNOWLEDGEMENTS

The authors wish to extend their thanks for the support provided by the Ibnu Sina Institute, Universiti Teknologi Malaysia, Malaysia and Nano-Optoelectronics Laboratory, Universiti Sains Malaysia, Malaysia. This work was supported by the Ministry of Science, Technology and Innovation under Science-Fund Grant 03-01-06-SF0277, Malaysia government. We wish to thank our colleagues for useful discussions, particularly, Assoc. Prof. Dr Zulkafli Othman at Universiti Teknologi Malaysia, Malaysia and Assoc. Prof Dr Zhang Dao Hua at Nanyang Technological University, Singapore.

REFERENCES

1. Hasegawa, H., 2003. Formation of III-V Low Dimensional Structures and Their Applications to Intelligent Quantum Chips. Microelectronics J., 34(5): 341-345.
2. Sharma, B.L., 1984. Metal-Semiconductor Schottky Barrier Junctions and Their Applications. Plenum Press, New York and London.
3. Suh, Y.H. and K. Chang, 2002. A High-Efficiency Dual-Frequency Rectenna for 2.45- and 5.8-GHz Wireless Power Transmission. IEEE Transactions on Microwave Theory Techniques, 50(7): 1784-1789.
4. Hashim, A.M., S. Kasai, T. Hashizume and H. Hasegawa, 2007. Integration of Interdigital-Gated Plasma Wave Device for Proximity Communication System Application. Microelectronics J., 38(12): 1263-1267.
5. Hashim, A.M., S. Kasai, T. Hashizume and H. Hasegawa, 2007. Novel Structure of GaAs-Based Interdigital-Gated HEMT Devices for Solid-State THz Wave Amplifier. Microelectronics J., 38(12): 1268-1272.
6. Hashim, A.M., S. Kasai and H. Hasegawa, 2008. Observation of Third Harmonics Response In Two-Dimensional AlGaAs/GaAs HEMT Devices Due to Plasma Wave Interaction. Superlattices and Microstructures, 44: 754-760.
7. Wen, C.P., 1969. Coplanar Waveguide: A Surface Strip Transmission Line Suitable for Nonreciprocal Gryromagnetic Device Applications. IEEE Transactions on Microwave Theory Techniques, 17(12): 1087-1088.
8. Jeon, W., T.M. Firestone, J.C. Rodgers and J. Melngailis, 2004. Design and Fabrication of Schottky Diode On-Chip RF Power Detector. Solid State Electronics, 48: 2089-2093.
9. Mustafa, F., N. Parimon, A.M. Hashim, S.F.A. Rahman, A.R.A. Rahman, M.N. Osman, 2010. Design, Fabrication and Characterization of a Schottky Diode on an AlGaAs/GaAs HEMT Structure for On-Chip RF Power Detection. Superlattices and Microstructures, 47: 274-287.