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2011 IOP Conf. Ser.: Mater. Sci. Eng. 17 012023

(http://iopscience.iop.org/1757-899X/17/1/012023)

IOP Conf. Series: Materials Science and Engineering **17** (2011) 012023 doi:10.1088/1757-899X/17/1/012023

Fabrication and Characterization of Planar Dipole Antenna Integrated with GaAs Based-Schottky Diode for On-chip Electronic Device Application

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Abstract The design and RF characteristics of planar dipole antennas facilitated with coplanar waveguide (CPW) structure on semi-insulated GaAs are performed and confirmed to work in super high frequency (SHF) range. As expected, the fundamental resonant frequency shifts to higher frequency when the length of antenna decreases. Interestingly, the resonant frequencies of antenna are almost unchanged with the variation of antenna width and metal thickness. It is shown experimentally that return loss down to -54 dB with a metal thickness of 50 nm is obtainable. 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 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. These preliminary results provide a new breakthrough for on-chip electronic device application in nanosystems.

1. Introduction

The "New IT Reform Strategy" is put in motion as a national strategy with an aim of realizing "a society in which everyone can feel the benefit of IT whenever and wherever," namely, a ubiquitous network society. The development of appropriate antennas and associated technology will be important to the success of millimeter-wave wireless personal communication systems. This wireless system would be the groundwork for ubiquitous network society [1]. Research in these areas and also on the processes of indoor propagation has been carried out with particular emphasis on integrating antennas with multifunction GaAs monolithic microwave integrated circuits (MMIC's) [2]. As it is well known, planar antennas consisting of dipoles, patches or slots, fed by a microstrip transmission line, are extremely useful due to their low cost, light weight and flexibility of design [3].

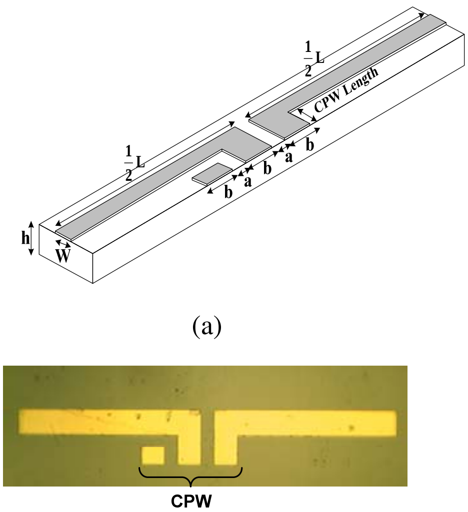
Indeed, for components including active devices, in particular, MMIC's, the popularity of coplanar waveguide (CPW) has increased significantly in recent years because the advantages of CPW like wider bandwidth, smaller mutual coupling between two adjacent lines, and easier integration with solid-state active devices on one side of the planar substrate, thus avoiding via hole connections [4].

Current advancements in communication technology and significant growth in the wireless communication market and consumer demands demonstrate the need for smaller, more reliable and power efficient, integrated wireless systems. Integrating entire transceivers on a single chip is the vision for future wireless systems. This has the benefit of cost reduction and improving system reliability. Antennas are considered to be the largest components of integrating wireless systems [5]. In wireless systems, the distance between the antenna and the detector circuit must be made as short as possible in order to prevent transmission lost in the feed line such as CPW [6]. In addition the antenna integrated on the same substrate can be made well-matched with good efficiency and improved bandwidth [7].

In this paper, we present the design and RF characteristics of planar dipole antenna facilitated with CPW structure on semi-insulated high-dielectric constant substrate, GaAs which ε_r = 12.9 in millimeter-wave region. We also present the preliminary experimental results of integrated dipole antenna and Schottky diode fabricated on n-AlGaAs/GaAs HEMT structure without any matching circuit inserted towards realization of ubiquitous network society.

2. Antenna Design

As the popularity of the CPW transmission line has increased significantly in recent years, antenna elements that are suitable for CPW feed configuration have also become important. In light of this, a design guideline for the CPW-fed antenna is presented herein. Figure 1(a) shows the proposed dipole antenna structure facilitated with CPW as transmission line within the same dielectric substrates. The fabricated dipole antenna is shown in Figure 1(b).



(a)

(b)

Figure 1. (a) Schematic dipole antenna structure and (b) fabricated dipole antenna.

The dipole antenna structure is implemented on semi-insulated high dielectric substrates, GaAs with thickness of 625 μm, a dielectric constant ε_r = 12.9 and a loss tangent of *tan* δ = 0.001. For almost application today, dipole antennas are easy to build and install and they give good results. The advantages of this type of planar dipole antenna are its small dimension and the ease of manufacturing, making it a low-cost antenna.

The dimensions of the gap, *a* and width, *b* for CPW calculated based on the Wheeler's equation [8] are also chosen to be 60 μm and 90 μm, respectively, for the characteristic impedance, Z_o of 50 Ω. The thickness, *h* is 625 μm. The dependence of characteristic impedance as a function of gap and width is shown in Figure 2. This CPW structure also suits to the dimension of Cascade G-S-G microprober used in the measurement process. The length of the CPW is chosen to be 120 μm. It is noticed here that longer CPW length may affect the resonant frequency of the dipole antenna based on our separate pre-simulation results on the CPW analysis using commercial Electromagnetic (EM) Sonnet Suites simulator which is full wave EM simulation software. Therefore, shorter CPW length is chosen in order to omit any matching circuit during the direct integration. Besides that, it also can reduce specific area for making it a low cost antenna.

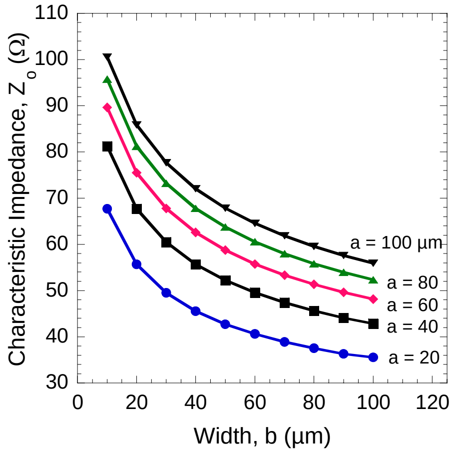


Figure 2. Characteristic impedance of CPW as a function of gap and width.

The metals of the antenna are Cr/Au with a thickness of 10/60 nm. Basically, Cr, Ni and Au are used to make link between antenna and Schottky contact because most of Schottky contact for GaAs-based devices are made using Cr/Au or Ni/Au. Thus, it can reduce step in fabrication when the integration of antenna and Schottky diode is performed. In this study, S-Parameter reflection measurement on the fabricated dipole antenna in microwave region at room temperature is performed to characterize the return loss of the CPW facilitated planar dipole antenna. An HP8722S Vector Network Analyzer in conjunction with GSG Cascade microprober Infinity-150 is used in this measurement process.

3. Simulation and experimental results

In this study, the dipole antenna structures is investigated by varying the length, *L* and width, *W* of the antenna and those designed antennas are working in the super high frequency (SHF) band range. The example of typical return loss characteristics is shown in Figure 3. From the graph obtained, for the antenna length of 3 mm and width of 90 μm, there is almost 4 % difference of frequency bandwidth at -10 dB between the measured and simulated response. Such small discrepancy is commonly observed [5] due to a variation in parameter such as the loss tangent for the fabricated device whereas a simulator is dealing with an ideal parameter. Here, it can also be clearly seen that very high return loss magnitude down to -46 dB at 18 GHz is experimentally obtained.

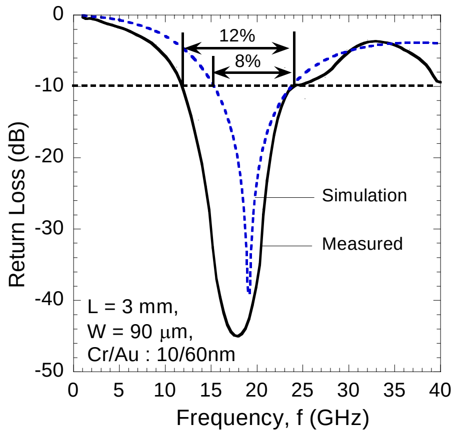


Figure 3. Measured and simulated return loss for CPW-fed dipole antenna with L = 3 mm and W = 90 μm.

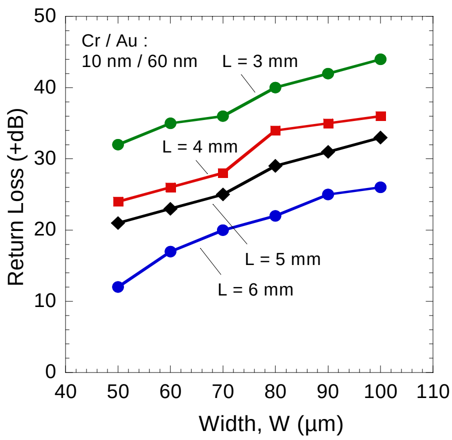


Figure 4. Positive magnitude of return loss at fundamental resonant frequency as a function of antenna width for various lengths.

The positive magnitude of return loss characteristics at fundamental resonant frequency as a function of antenna width for various lengths is shown in Figure 4. High return loss obtained makes the antenna become more meaningful and also improves the integration with other microwave device. Consequently, it will reduce the quantity of reflected signal. It is noted that, to decrease return loss and increase resonance frequency, the shorter length of antenna should be used in order to get better performance.

Figure 5 shows the characteristics of the antenna as a function of resonant frequency for various dimensions of width. As shown in Figure 5, the resonant frequencies of antenna are almost unchanged with the variation of antenna width. To put in a nutshell, changing width of antenna does not influence much on the position of the resonant frequency. From Figure 5, it is shown that the width dependence only has an effect on the magnitude of return loss as expected. To get higher magnitude of return loss, wider width of dipole antenna should be applied.

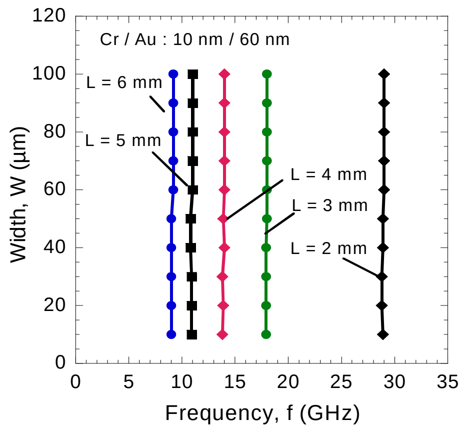


Figure 5. Characteristics of the antenna as a function of resonant frequency for various values of width.

In this study, to verify the simulation and measurement result, the calculation on the resonant frequency of those dipole antennas is determined using equation for microstrip dipole antenna presented in Ref. [9]. The effective dielectric constant, ε_{eff} constant of a microstrip line is:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\frac{1}{\sqrt{1 + \frac{12h}{W}}}\right] \qquad (1)$$

In Eq. (1), ε_r is the dielectric constant and h is the substrate thickness of microstrip. The length of antenna, L can be calculated using formula:

$$L = \frac{\lambda}{2} = \frac{c}{f_r \sqrt{\varepsilon_{eff}}} \qquad (2)$$

In Eq. (2), λ is the wavelength, c is the velocity of light and f_r is the resonant frequency. It can be seen here that the experimental result is in good agreement with the calculated result as shown in Figure 6. As expected, it can be seen in Figure 6 that the fundamental resonant frequency shifts to higher frequency when the length of antenna decreases.

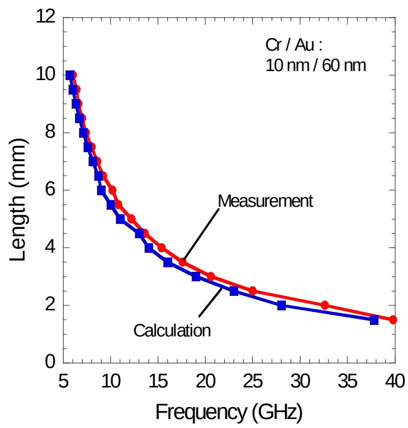


Figure 6. Characteristics of the antenna as a function of resonant frequency for various values of length.

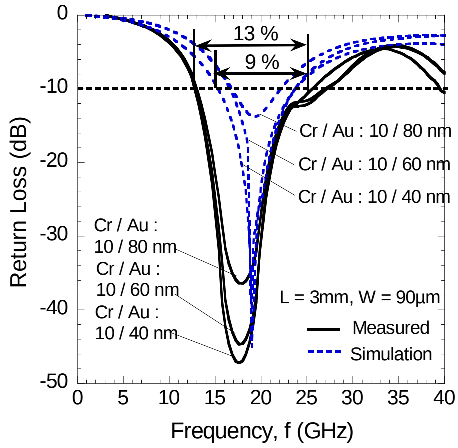


Figure 7. Measured and simulated return loss as a function of resonant frequency with various metal thickness.

In our work, we noticed that metal thickness also affected the antenna performance particularly on return loss characteristic. The dipole antenna is deposited with different metal thickness to prove our assumption. The metals of the antenna are Cr/Au with thickness of 10/40 nm, 10/60 nm and 10/80 nm. Figure 7 shows the example of measured and simulated return loss as a function of resonant frequency with different metal thickness. It can be clearly seen that there is only 4 % frequency shift between the measured and simulated response at -10 dB bandwidth. Here, also similar tendency of discrepancy shown in Figure 3 is obtained. High return loss characteristic down to -48 dB with a metal thickness of 50 nm is obtainable. It is shown that the return loss increase if metal thickness decrease. The resonant frequencies of antenna are almost unchanged with the variation of metal thickness.

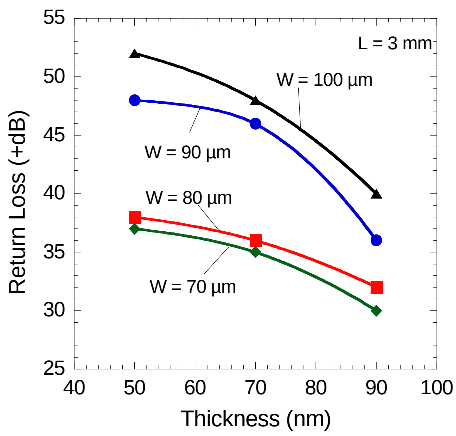
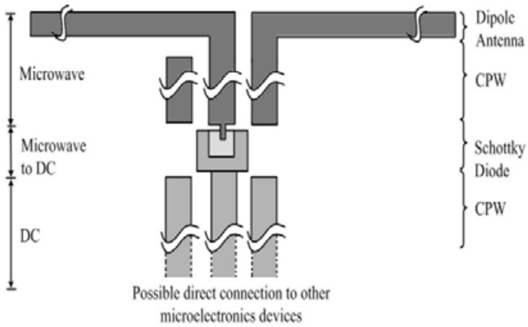


Figure 8. Positive magnitude of return loss at fundamental resonant frequency as a function of metal thickness for various widths.

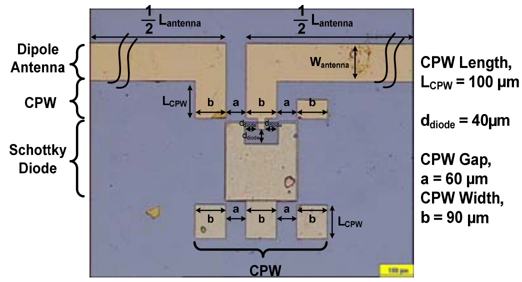
Figure 8 shows the positive magnitude of return loss at fundamental resonant frequency as a function of metal thickness for various widths. This graph shows the effect of metallization thickness on return loss characteristics of dipole antenna structure. Therefore, it is advisable to include this factor when designing antenna structure.

4. Integration of dipole antenna and Schottky diode

The possible direct connection between dipole antenna and Schottky diode designed on the same substrate is illustrated in Figure 9(a). Based on the design and obtained results of the dipole antenna presented before and Schottky diode presented in Ref. [10], it is expected that direct integration via short CPW transmission line between dipole antenna and Schottky diode can be achieved without any matching circuit. For this purpose the behavior of the dipole antenna and Schottky diode have to be modeled at and around the operating frequency. Since all the components are designed on the same substrate, a planar fabrication technique can guarantee excellent mechanical tolerances as well as tuning-free design. The measured results show the usefulness of the proposed antenna configuration and the effectiveness of uniplanar technology both in terms of performance and cost.



(a)



(b)

Figure 9. (a) Schematic and (b) fabricated devices of direct integration between dipole antenna and Schottky diode.

The integrated dipole antenna and Schottky diode device without insertion of matching circuit as illustrated in Figure 9(a) is fabricated using standard photolithography and lift-off process. Figure 9(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 previous section, 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.

a) 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. The schematic of the Schottky diode is shown in Figure 10. Figure 11 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 11 (inset). The reverse leakage current for the fabricated devices is 399 nA and SBH was calculated to be 0.4095 eV.

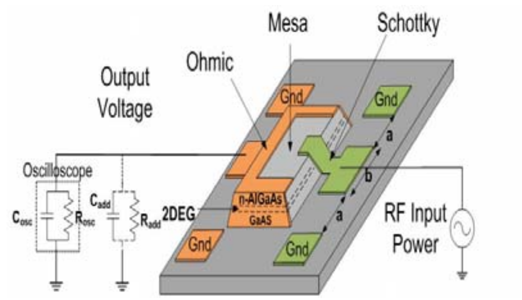


Figure 10. Schematic structure of Schottky diode.

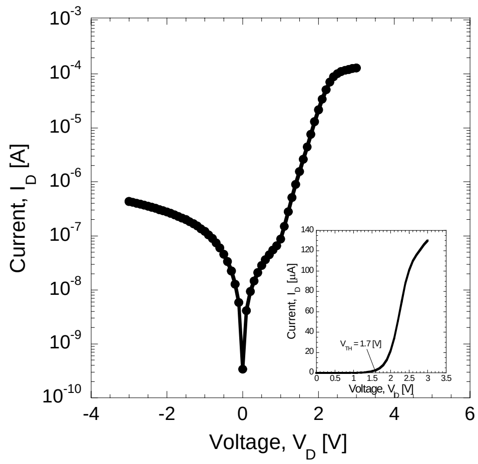


Figure 11. DC *I-V* Curve of the fabricated device.

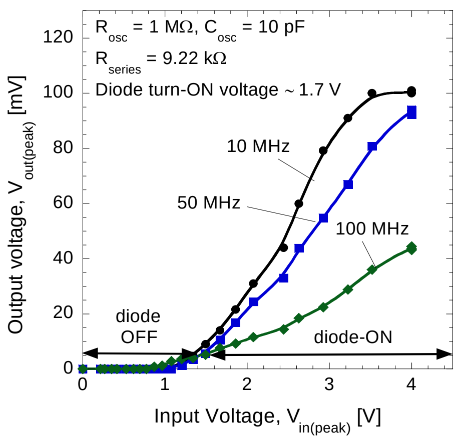


Figure 12. Rectified output voltages as a function of input voltages for R_{osc} = 1 MΩ and C_{osc} = 10 pF at different frequency.

The RF-DC conversion characteristics of Schottky diode was investigated using oscilloscope connected at the output side as shown in Figure 10. Figure 12 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.

b) Direct RF irradiation

An experimental set-up for the direct RF irradiation is shown in Figure 13. 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 13. Spectrum analyzer is used to measure the reception of RF power before entering Schottky diode.

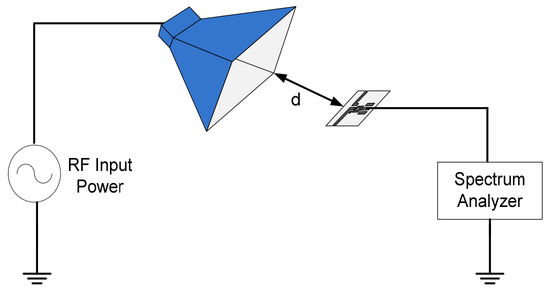
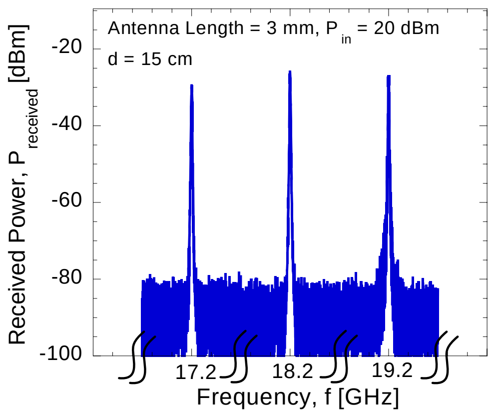


Figure 13. Direct irradiation measurement setup.

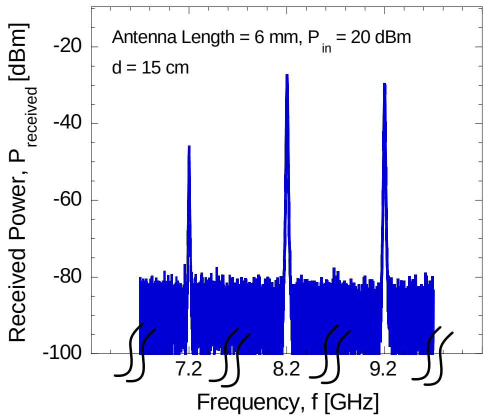
Figure 14(a) and (b) show the received power as a function of frequency for antenna length of 3 mm and 6 mm, respectively. It was confirmed that the resonant frequency of antenna with length of 3 mm and 6 mm is 18.2 GHz and 8.2 GHz. Therefore, maximum power should be received by antenna at these frequencies. However, it can be seen that weak signal reception around -30 dBm was measured for both devices as shown in Figure 14(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, 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 14. When the dipole antenna is integrated with the diode, the output signal becomes weaker than that of diode.



(a)



(b)

Figure 14. Generated received power as a function of frequency for antenna length of (a) 3 mm and (b) 6 mm.

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.

5. Conclusion

In this paper, planar dipole antenna with CPW feed as transmission line was successfully designed and analyzed for working in super high frequency band range. From the result obtained, the dipole antennas showed high return loss characteristics and their fundamental resonant frequency can be controlled by dipole length but unchanged with the width and metal thickness. 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 RF power detector and 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 and Nano-Optoelectronics Laboratory, Universiti Sains Malaysia. This work was supported by the Ministry of Science, Technology and Innovation under Science Fund Grant 03-01-06-SF0277. We wish to thank our colleagues for useful discussions, particularly, Assoc. Prof. Dr Zulkafli Othaman from Universiti Teknologi Malaysia, Malaysia.

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