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Design of a 94-GHz Single Balanced Mixer Using Planar Schottky Diodes with a Nano-Dot Structure on a GaAs Substrate

Won-Young Uhm[1], Keun-Kwan Ryu[2], and Sung-Chan Kim[2*], *Member, KIICE*

[1]Division of Electronics and Electrical Engineering, Dongguk University, Seoul 04620, Korea
[2]Department of Electronics and Control Engineering, Hanbat National University, Daejeon 34158, Korea

Abstract

In this paper, we develop a 94-GHz single balanced mixer with low conversion loss using planar Schottky diodes on a GaAs substrate. The GaAs Schottky diode has a nanoscale anode with a T-shaped disk that can yield high cutoff frequency characteristics. The fabricated Schottky diode with an anode diameter of 500 nm has a series resistance of 21 Ω, an ideality factor of 1.32, a junction capacitance of 8.03 fF, and a cutoff frequency of 944 GHz. Based on this technology, a 94-GHz single balanced mixer was constructed. The fabricated mixer shows an average conversion loss of -7.58 dB at an RF frequency of 92.5 GHz to 95 GHz and an IF frequency of 500 MHz with an LO power of 7 dBm. The RF-to-LO isolation characteristics were greater than -32 dB. These values are considered to be attributed to superior Schottky diode characteristics.

Index Terms: Anode, GaAs, Nanoscale dot, Schottky diode, Single balanced mixer

I. INTRODUCTION

In order to realize various millimeter-wave and terahertz applications, high performance monolithic millimeter-wave integrated circuit (MMIC) mixers are very important. Although millimeter-wave mixer techniques are well developed, the high-performance monolithic mixer remains an ongoing research topic. In particular, Schottky diode mixers with the single balanced configuration continue to be developed due to their advantages such as simplicity of circuit structure, compared with the double balanced configuration, and good LO-to-RF isolation characteristics [1-3].

The Schottky diode is a majority-carrier device that does not suffer from charge-storage effects, and therefore it provides good and uniform electrical characteristics. Furthermore, the fabrication process for the Schottky diode is comparatively easy while still allowing for implementtation of other devices on the same substrate. Most Schottky diodes for high frequency applications use a circular anode with an air bridge that connects the anode to the ohmic contact. As the anode diameter is reduced for higher frequency operation, the series resistance increases and the width of the air bridge becomes larger than the anode diameter. These changes cause degradation of the diode performance as well as physical instability for diode fabrication.

In this paper, we report on the development of a Schottky diode with a nanoscale anode and a T-shaped disk on a GaAs substrate for millimeter-wave and terahertz

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***Corresponding Author** Sung-Chan Kim (E-mail: sckim@hanbat.ac.kr, Tel: +82-42-821-1130)
Department of Electronics and Control Engineering, Hanbat National University, 125 Dongseo-daero, Yuseong-gu, Daejeon 34158, Korea.

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applications. Based on this technology, we present a low conversion loss, single-balanced MMIC mixer for 94 GHz applications.

II. CHARACTERISTICS OF THE PLANAR SCHOTTKY DIODE

The Schottky diode is the critical element used in a mixer for a variety of applications in the millimeter-wave and terahertz frequency range. To achieve the low conversion loss characteristics of the mixer, the operating frequency should be significantly lower than the diode's cutoff frequency. The diode cutoff frequency is defined as (1).

$$f_c = \frac{1}{2\pi R_s C_{j0}} \tag{1}$$

In (1), R_s is the DC measured series resistance at a large forward bias, and C_{j0} is the junction capacitance at a zero bias. Reducing the anode diameter reduces the junction capacitance but increases the series resistance. As a result, complicated trade-offs are involved in choosing an anode size. Reducing the anode diameter was found to show better performance at high frequency [4]. A similar analysis using the R_sC_{j0} product indicates that the optimum anode diameter maximizes the cutoff frequency for each epitaxial layer doping density [5]. Therefore, we calculated the series resistance and the junction capacitance as a function of the anode diameters. From the simulated results, we concluded that the suitable anode diameter was 500 nm, considering optimized R_s and C_{j0} as well as the process stability.

The epitaxial structures for the Schottky diodes were grown on a 4-inch semi-insulating GaAs substrate by using molecular beam epitaxy (MBE). GaAs buffer layers with a thickness of 300 nm were grown on the GaAs substrate. The ohmic layers were grown with a thickness of 300 nm with Si doping ($6 \times 10^{18}/cm^3$) for the ohmic contact. The top of the epitaxial layer was grown with a thickness of 350 nm with Si doping ($1 \times 10^{17}/cm^3$) for the Schottky contact.

The Schottky diode was fabricated using the heterogeneous resist patterning method. Because the photo lithography process is unsuitable for nanoscale patterning, we performed nano-dot patterning using the e-beam lithography process. The nanoscale dot as the anode is used for the Schottky contact, and the T-shaped disk is used to connect the anode to the air bridge. The e-beam lithography process uses multiple e-beam scans at different doses and a tri-level e-beam resist system that consists of PMMA-950K and PMGI in order to separately pattern the nanoscale dot and the T-shaped disk of the diode anode. After metallization for the diode anode, the air-bridge process was performed by photo lithography in order to connect the anode with the anode pad. Fig. 1 shows a scanning electron microscope (SEM) photograph of the fabricated Schottky diode with a nano-dot structure. Fig. 2 shows a close-up of the fabricated nanoscale dot and T-shaped disk.

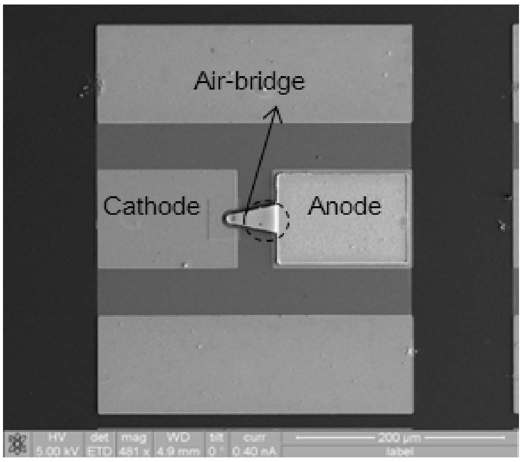

Fig. 1. SEM photograph of the fabricated Schottky diode: top view.

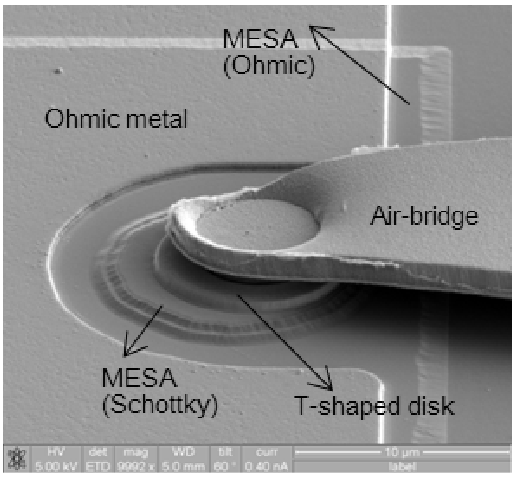

Fig. 2. SEM photograph of the fabricated Schottky diode: close-up of the cathode area.

The I–V characteristics of the fabricated Schottky diode were measured using a Keithley 4200-SCS (semiconductor characterization system). The ideality factor (η), current parameter (I_0), and series resistance (R_s) can be obtained from measurement of the I–V characteristics. Fig. 3 shows the I–V characteristics of the fabricated Schottky diodes. Extraction of the series resistance of the Schottky diode can be done using the saturation current method. The ideality factor was also obtained by calculating the voltage deviation between the fitting line and the measured I–V curve. The calculated series resistance and the ideality factor with an anode diameter of 500 nm were 21.0 Ω and 1.32, respectively.

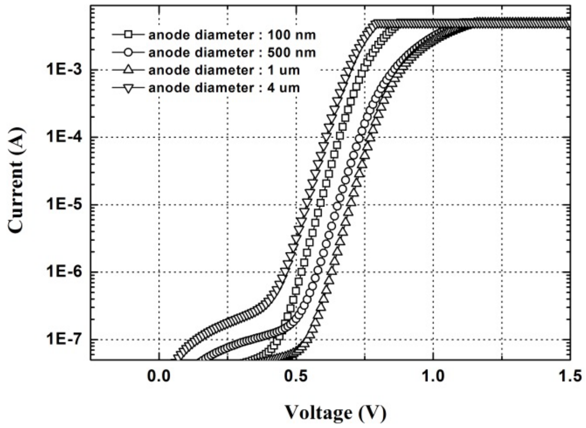

Fig. 3. Measured I-V characteristics of the fabricated Schottky diodes.

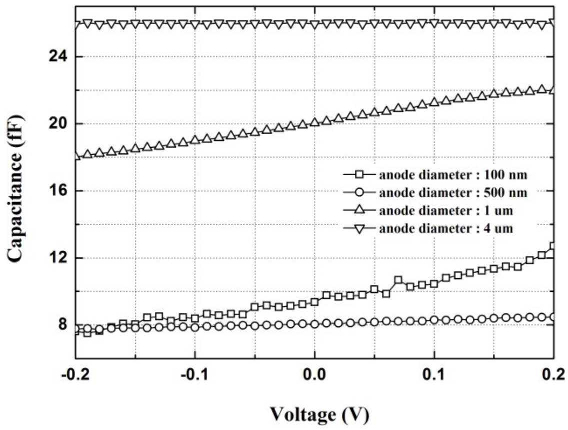

Fig. 4. Measured junction capacitance characteristics of the fabricated Schottky diodes.

The capacitance-voltage characteristics were measured using an Agilent E4980A Precision LCR Meter. Fig. 4 shows the measured junction capacitance characteristics. The measured total junction capacitance (C_{j0}) with an anode diameter of 500 nm is 8.03 fF at the zero-bias condition. The cut-off frequency can be calculated using the obtained series resistance and the junction capacitance. The calculated cut-off frequency is 944 GHz.

III. PERFORMANCE OF THE 94 GHZ SINGLE BALANCED MIXER

A circuit diagram of the designed 94 GHz single balanced mixer is shown in Fig. 5. The 94 GHz single balanced diode mixer consists of two Schottky diodes with an anode diameter of 500 nm, a tandem coupler, and a band reject filter. A tandem coupler as a W-band balun was used for high LO-to-RF isolation. A quarter wavelength at the LO

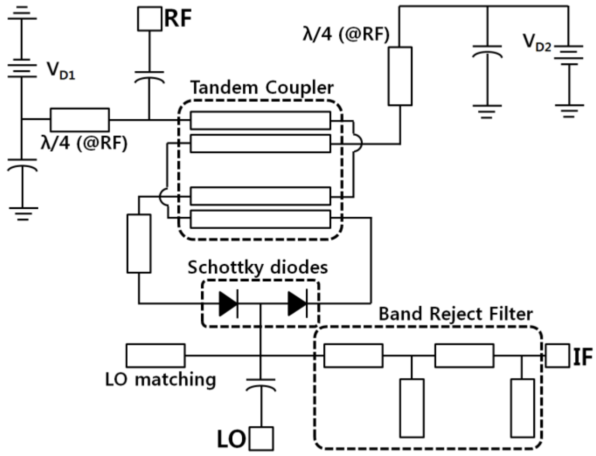

Fig. 5. Schematic circuit diagram of the developed 94 GHz single balanced mixer.

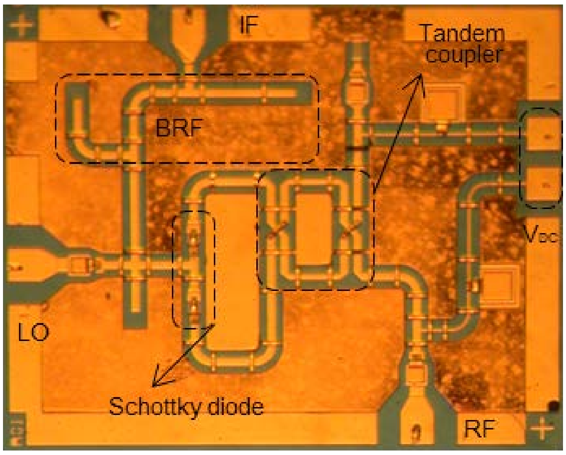

Fig. 6. SEM photograph of the fabricated 94 GHz single balanced mixer.

line was designed to ensure a 180° phase difference between the RF and the LO ports. The LO and RF signals were directed through the metal-insulator-metal (MIM) capacitors, while a band reject filter for suppressing the LO signal was used at the intermediate frequency (IF) stage to extract the desired IF signal.

The designed 94 GHz single balanced mixer was fabricated using the standard MMIC process from the Millimeter-Wave Innovation Research Center (MINT), Dongguk University [6]. Fig. 6 shows a SEM photograph of the fabricated 94 GHz single balanced mixer using Schottky diodes with an anode diameter of 500 nm. The total chip size is 1.9 mm × 1.3 mm.

We measured the conversion loss and isolation characteristics of the fabricated mixer by using an Agilent E4407B spectrum analyzer with a 11970W harmonic mixer, an 83558A millimeter-wave source module, voltage-controlled

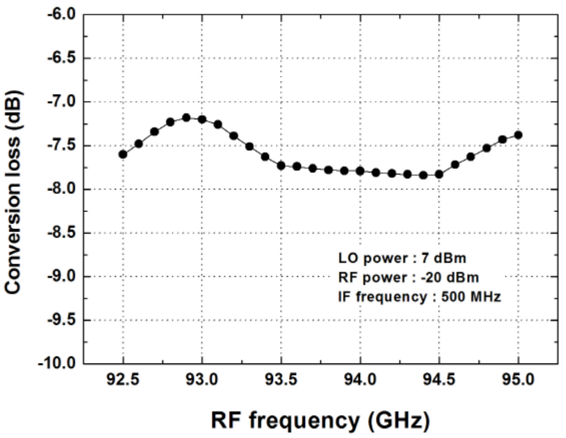

Fig. 7. Measured conversion loss characteristics of the fabricated 94 GHz single balanced mixer.

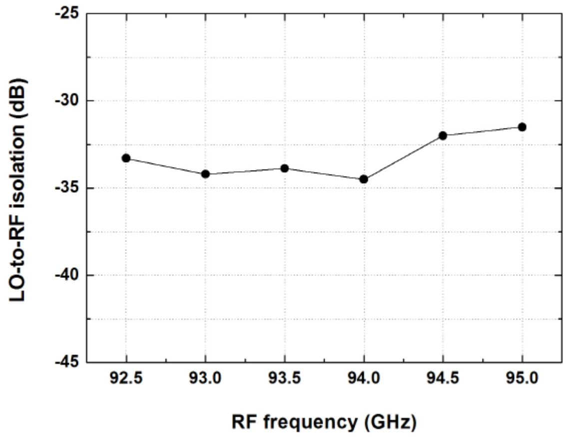

Fig. 8. Measured LO-to-RF isolation characteristics of the fabricated 94 GHz single balanced mixer.

oscillators, and GGB110H probes at a frequency range from 92.5 GHz to 95 GHz. The fabricated mixer had an average conversion loss of -7.58 dB at an RF frequency of 92.5 GHz to 95 GHz with an IF frequency of 500 MHz with an LO power of 7 dBm, as shown in Fig. 7. The RF-to-LO isolation characteristics were greater than -32 dB as shown in Fig. 8.

Finally, Table 1 shows a comparison of the W-band MMIC mixers with other published data. Considering the low LO power, the mixer presented in this paper showed a good conversion loss of 7.8 dB at 94 GHz. This improvement can be attributed to the superior Schottky diode characteristics. The fabricated Schottky diode with a nanoscale anode is expected to be applied to terahertz applications.

IV. CONCLUSION

In this paper, we developed a 94 GHz low conversion loss, single balanced mixer using planar Schottky diodes on a GaAs substrate. The GaAs Schottky diode has a nanoscale anode with a T-shaped disk, which can yield high cutoff frequency characteristics. The fabricated Schottky diode with an anode diameter of 500 nm exhibits an ideality factor of 1.32, a junction capacitance of 8.03 fF, and a cutoff frequency of 944 GHz. Based on this technology, a 94 GHz single balanced mixer was built. The fabricated mixer shows an average conversion loss of -7.58 dB at an RF frequency of 92.5 GHz to 95 GHz with an IF frequency of 500 MHz and a LO power of 7 dBm. The RF-to-LO isolation characteristics are greater than -32 dB. These values can be attributed to the superior Schottky diode characteristics.

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REFERENCES

[1] S. A. Maas, *Microwave Mixers*, 2nd ed. Boston, MA: Artech House, 1993.
[2] C. Florian, F. Scappaviva, M. Feudale, V. A. Monaco, and F.

Table 1. Comparison of the W-band MMIC mixer with other published data

Circuit technology	Frequency (GHz)	Conversion loss (dB)	LO power (dBm)	LO-to-RF isolation (dB)	Ref.
GaAs MHEMT diode mixer	91–96	7.0–7.8	8.6	30–40	[7]
GaAs MESFET diode mixer	94	11.4	10	-	[8]
GaAs PHEMT mixer	92–96	<12	8	>27	[9]
GaAs Schottky diode mixer	94	8.8	4.2	27	[10]
GaAs Schottky diode mixer	92.5–95	7.2–7.8	7	32–34.5	This work

Filicori, “A V band singly balanced diode mixer for space application,” in *Proceedings of European Gallium Arsenide and Other Semiconductor Application Symposium (EGAAS2005)*, Paris, pp. 441-444, 2005.

[3] Z. Y. Zhang, Y. R. Wei, and K. Wu, “Broadband millimeter-wave single balanced mixer and its applications to substrate integrated wireless systems,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 3, pp. 660-669, 2012.

[4] U. V. Bhapkar and T. W. Crowe, “Analysis of the high frequency series impedance of GaAs Schottky diodes by a finite difference technique,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 40, no. 5, pp. 886-894, 1992.

[5] T. W. Crowe, W. C. B. Peatman, P. A. D. Wood, and X. Liu, “GaAs Schottky barrier diodes for THz applications,” in *Proceedings of IEEE MTT-S International Microwave Symposium Digest*, Albuquerque, NM, pp. 1141-1144, 1992.

[6] K. K. Ryu, S. C. Kim, D. An, and J. K. Rhee, “High-performance CPW MMIC LNA using GaAs-based metamorphic HEMTs for 94-GHz applications,” *Journal of the Korean Physical Society*, vol. 56, no. 5, pp. 1509-1513, 2010.

[7] M. K. Lee, B. O. Lim, S. J. Lee, D. S. Ko, S. W. Moon, D. An, et al., “A novel 94-GHz MHEMT-based diode mixer using a 3-dB tandem coupler,” *IEEE Microwave and Wireless Components Letters*, vol. 18, no. 9, pp. 626-628, 2008.

[8] K. Kanaya, K. Kawakami, T. Hisaka, T. Ishikawa, and S. Sakamoto, “A 94 GHz high performance quadruple subharmonic mixer MMIC,” in *Proceedings of IEEE MTT-S Interntional Microwave Symposium Digest*, Seattle, WA, pp. 1249-1252, 2002.

[9] A. R. Barnes, P. Munday, R. Jennings, and M. T. Moore, “A comparison of W-band monolithic resistive mixer architectures,” in *Proceedings of IEEE MTT-S International Microwave Symposium Digest*, Seattle, WA, pp. 1867-1870, 2002.

[10] H. Matsuura, K. Tezyka, I. Aoki, A. Miura, M. Yamanaka, T. Yakihara, et al., “A monolithic W-band CPW rat-race mixer with HBT IF amplifier,” in *Proceedings of IEEE MTT-S International Microwave Symposium Digest*, San Francisco, CA, pp. 389-392, 1996.

Won-Young Uhm
received his B.S. and M.S. in Electrical Engineering from Dongguk University, Seoul, Korea, in 2002 and 2004, respectively. In 2004, he joined the Agency for Defense Development (ADD) as a senior research engineer. He is currently pursuing his Ph.D. at Dongguk University. His research interests include high-frequency integrated circuits using compound semiconductor technologies.

Keun-Kwan Ryu
received his B.S., M.S., and Ph.D. in Electronics and Communications Engineering from Kwangwoon University, Seoul, Korea, in 1992, 1994, and 2000, respectively. From 2001 to 2002, he was with the Electronics and Telecommunications Research Institute (ETRI) as a senior research engineer. In 2003, he joined the Department of Electronic Engineering, Hanbat National University, Daejeon, Korea, and is now a full professor. His research interests include high-frequency active and passive circuits.

Sung-Chan Kim
received his B.S., M.S., and Ph.D. in Electrical Engineering from Dongguk University, Seoul, Korea, in 1999, 2001, and 2006, respectively. In 2007, he joined the Department of Electronic Engineering, Hanbat National University, Daejeon, Korea, and is now an associate professor. His research interests include high frequency integrated devices and circuits using compound semiconductor technologies at microwave and millimeter-wave frequencies.