



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

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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 implementation 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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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).

$$f_c = \frac{1}{2\pi R_s C_{j0}} \quad (1)$$

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 $R_s C_{j0}$ 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 ($6 \times 10^{18}/\text{cm}^3$) for the ohmic contact. The top of the epitaxial layer was grown with a thickness of 350 nm with Si doping ($1 \times 10^{17}/\text{cm}^3$) 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

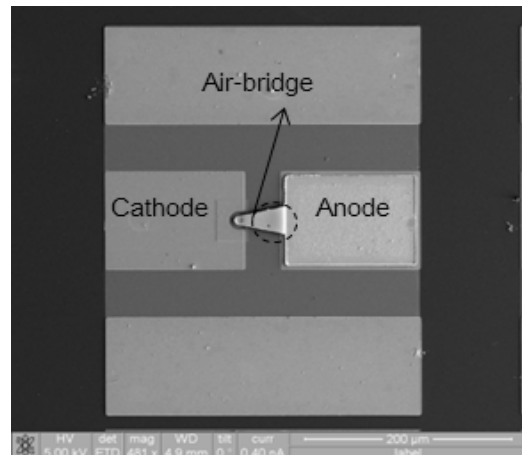


Fig. 1. SEM photograph of the fabricated Schottky diode: top view.

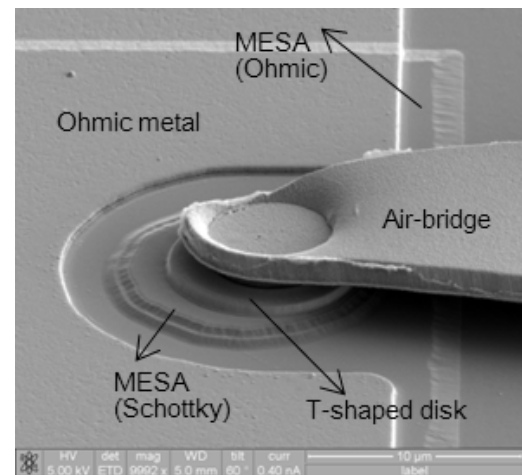


Fig. 2. SEM photograph of the fabricated Schottky diode: close-up of the cathode area.

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.

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.

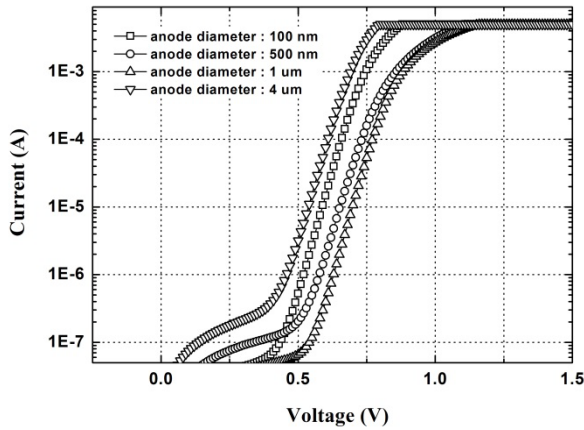


Fig. 3. Measured I-V characteristics of the fabricated Schottky diodes.

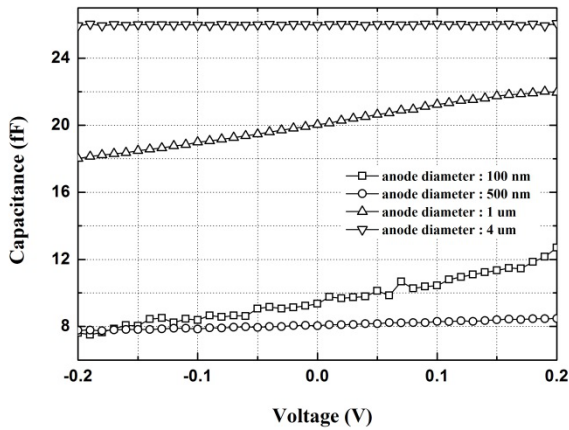


Fig. 4. Measured junction capacitance characteristics of the fabricated Schottky diodes.

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

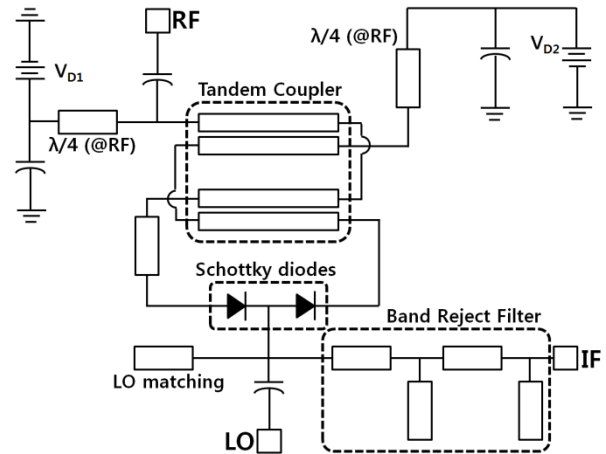


Fig. 5. Schematic circuit diagram of the developed 94 GHz single balanced mixer.

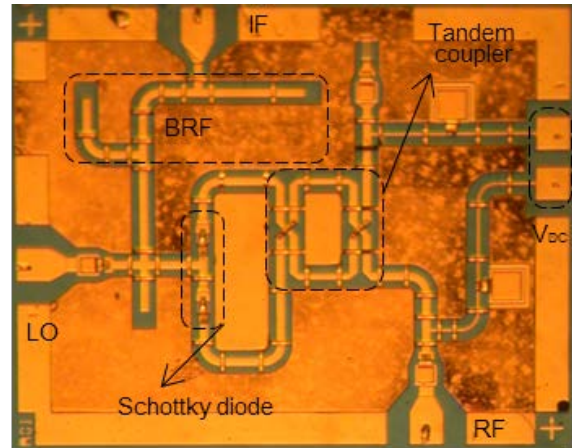


Fig. 6. SEM photograph of the fabricated 94 GHz single balanced mixer.

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 $1.9 \text{ mm} \times 1.3 \text{ mm}$.

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

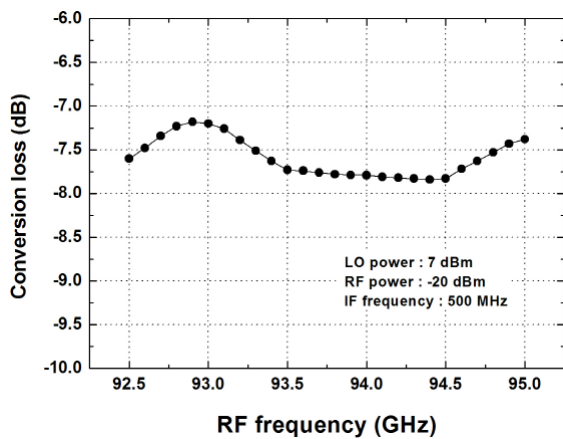


Fig. 7. Measured conversion loss characteristics of the fabricated 94 GHz single balanced mixer.

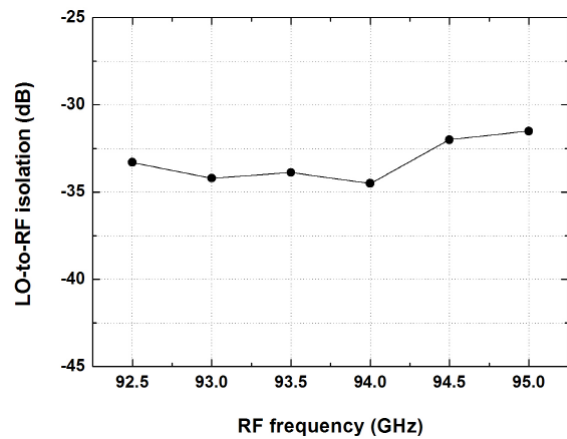


Fig. 8. Measured LO-to-RF isolation characteristics of the fabricated 94 GHz single balanced mixer.

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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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

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