Vol. 30, No. 4 Journal of Semiconductors April 2009

Microwave frequency detector at X-band using GaAs MMIC technology*

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Abstract: The design, fabrication, and experimental results of an MEMS microwave frequency detector are presented for the first time. The structure consists of a microwave power divider, two CPW transmission lines, a microwave power combiner, an MEMS capacitive power sensor and a thermopile. The detector has been designed and fabricated on GaAs substrate using the MMIC process at the X-band successfully. The MEMS capacitive power sensor is used for detecting the high power signal, while the thermopile is used for detecting the low power signal. Signals of 17 and 10 dBm are measured over the X-band. The sensitivity is 0.56 MHz/fF under 17 dBm by the capacitive power sensor, and 6.67 MHz / μV under 10 dBm by the thermopile, respectively. The validity of the presented design has been confirmed by the experiment.

Key words: MEMS; frequency; detector; microwave; power divider; frequency measurement

DOI: 10.1088/1674-4926/30/4/044009 **EEACC:** 2575

1. Introduction

Demand for broad-band wireless communication services has been increasing explosively, driving the surge of research and development activities for communication systems with higher compatibility and increased functionality. Microwave frequency detection is an important part of microwave applications and measurement technology. Instantaneous frequency detector offers high dynamic ranges, good sensitivity and high frequency measurement accuracy[1]. To date, various constructions of microwave frequency detector have been introduced. Most popular microwave frequency measurements are based on digital circuits[2], terminal devices, movable membrane or diodes. Complicated structures including MCU or computers are required in most digital circuit systems. Also diodes are sensitive to temperature variations and have problems with impedance match.

In this paper, an X-band microwave frequency detector is realized in micro-electromechanical system (MEMS) technology. The fabrication is compatible with monolithic microwave integrated circuit (MMIC) process. This detector is based on sensing the phase shift between the two coplanar waveguide (CPW) transmission lines linearly dependent on the frequency of the signal. The phase delay is detected by two kinds of microwave power sensors. In comparison with conventional detectors, the design has the advantages of planar structure, reliability and high power-handing capability and compatibility with the gallium arsenide (GaAs) MMIC technology.

2. Principle

2.1. Microwave frequency detector

The detector is composed of a microwave power divider, a microwave power combiner, two CPW transmission lines, a capacitive microwave power sensor and a thermopile. Divided through the microwave power divider, the signal transmits by two CPW transmission lines, and then a phase delay is produced. Thus, by measuring the phase delay, the frequency of the signal can be determined since the phase delay is a function of the frequency. Figure 1 shows a schematic drawing of the basic detector structure. The signal is divided in the three-port power divider. Then the output signals of the divider flow in the two transmission lines with different length and obtain a phase delay. The signal branches processed by the phase shifter structure are synthesized into one by a microwave power combiner. The magnitude of the synthesized power containing information about the phase delay is detected by the microwave power sensors.

The microwave frequency detector operates at X-band and the center frequency is at 10 GHz. This detector structure, which is based on CPW configuration fully utilizing its considerable design versatility, includes the microwave power divider, the power combiner and microwave power sensor, where the characteristic impedance of the line is 50 Ω. Since the efficiency of the structure is significantly influenced by the individual component's performance, elaborate design optimization for each component should first be done to suppress return loss, as well as to verify the experimental results of the individual components.

2.2. Phase shifter

A phase shifter is a key element in this designed X-band

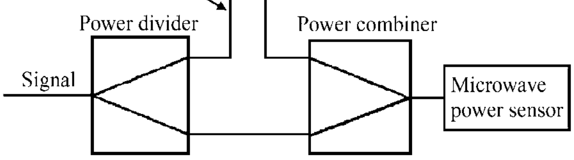

Fig. 1. Principle of X-band frequency detector.

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* Project supported by the National Natural Science Foundation of China (No. 60676043) and the National High Technology Research and Development Program of China (No. 2007AA04Z328).

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Received 23 September 2008

frequency detector. According to the theory of transmission, the phase delay of a transmission line can be expressed as

$$\frac{2\pi}{\lambda} = \frac{\theta}{L}, \tag{1}$$

where λ is the wavelength, θ is the phase delay, and L is the length of the transmission line. Then, the λ is a function of the frequency, giving

$$f = \frac{v}{\lambda} = \frac{c}{\sqrt{\varepsilon_{\mathrm{er}}}\lambda}, \tag{2}$$

where v is the propagation velocity of microwave， c is the velocity of light， and $\varepsilon_{\mathrm{er}}$ is the effective dielectric constant. Based on Eqs. (1) and (2), the relationship between the frequency and the phase delay can be given by

$$f = \frac{c}{2\pi\sqrt{\varepsilon_{\mathrm{er}}}L}\theta. \tag{3}$$

The length difference of the two transmission lines is selected to be $L = 3074$ μm at a target frequency of 10 GHz.

2.3. Microwave power sensor

In order to make the detector realize impedance match and offer a wide frequency detectable range, a capacitive microwave power sensor and a thermopile is adopted in this paper. The MEMS capacitive power sensor has an MEMS membrane over the center line of CPW, and two fixed electrodes located under the membrane. The other power sensor is a thermopile. It composes of fourteen thermocouples. The capacitive microwave power sensor has better performance measuring high power signals; while the thermopile is suited to measure low power signals. Also the thermopile plays an important role in impedance match at the end of the detector.

For the microwave power combiner, the synthesized microwave power can be deduced from the microwave theory and expressed as

$$U_{\mathrm{s}} = \sqrt{\left(\frac{1}{\sqrt{2}}U\right)^2 + \left(\frac{1}{\sqrt{2}}U\right)^2 + U^2\cos\theta}, \tag{4}$$

where U and U_{s} are the RMS voltage level of the divided branch power and synthesized power, respectively. The voltage virtual value U_{s} is simply deduced from $U_{\mathrm{s}}^2 = PZ_0$, where P and Z_0 are the synthesized power of signal and the impedance of the waveguide.

According to Eqs. (1)–(4), the frequency detection is finally determined by the power measurement.

The basic operation of the capacitive microwave power sensor is based on the capacitance between the MEMS membrane and the center line of CPW. Since the signal power and displacement of the movable membrane are both proportional to the square of the voltage level[3], a linear relation between the power and the displacement is found. The membrane ignored the inertial force and air damping force under the steady condition. The electrostatic force can be expressed as[4]

$$F_{\mathrm{e}} = kx, \tag{5}$$

where x is the displacement of the membrane and k is the elastic coefficient. When the microwave signal is transmitting through the sensor, the electrostatic force will pull the movable membrane towards the center line of CPW. The electrostatic force can be expressed as

$$F_{\mathrm{e}} = \frac{1}{2}\frac{\varepsilon_0 L_2 w U_{\mathrm{s}}^2}{(g_0 + g_1/\varepsilon_r - x)^2}, \tag{6}$$

where F_{e} is the electrostatic force, L_2 is the width of the center line, g_0 is the initial height of the air gap, g_1 is the thickness of the dielectric layer, w is the width of the membrane, and U_{s} is the RMS of the microwave signal. The capacitance between the membrane and the two fixed electrodes changes when the signal is applied on the membrane. It can be written as

$$C = \frac{\varepsilon_0 L_3 w}{g_0 + g_1/\varepsilon_{\mathrm{r}} - x}, \tag{7}$$

where L_3 is the width of the electrode. The fringing capacitance is ignored. The capacitance can be measured, and then the magnitude of U_{s} can be obtained by Eqs. (5)–(7).

The thermopile is based on the thermoelectric conversion effect. The microwave power is introduced by CPW and then it is absorbed by the load resistors. The absorbed power is converted into DC output voltage according to Seebeck effect. The output voltage and the sensitivity of the thermopile are expressed respectively as[5]

$$V_{\mathrm{out}} = \alpha\sum_{i}^{Ni}(T_{\mathrm{h}} - T_{\mathrm{c}}), \tag{8}$$

$$S_{\mathrm{th}} = V_{\mathrm{out}}/P_{\mathrm{bias}}, \tag{9}$$

where α is the Seebeck coefficient, P_{bias} is the microwave power dissipated by the matched resistance, and T_{h} and T_{c} are the temperature of the hot and cold junction of each thermocouple, respectively. The total sensitivity for the microwave power sensor is obtained by

$$S_{\mathrm{total}} = V_{\mathrm{out}}/P_{\mathrm{total}} = \alpha\sum_{i}^{Ni}(T_{\mathrm{h}} - T_{\mathrm{c}})/P_{\mathrm{total}}, \tag{10}$$

where P_{total} is the total microwave power transmitting on the CPW line. Since the voltage is proportional to the microwave power, the relationship between the voltage and the microwave power is found.

The detailed design and dimensions are chosen for the realization of the impedance match. Also a careful design is needed to prevent self-heating due to dissipation of the microwave signal. The individual component including the power divider, and the power sensors are designed to realize impedance match. In this case, the width of CPW is G/W/G = 58/100/58 μm. In order to miniaturize the power divider and the combiner, ACPS structure is adopted[6]. In the capacitive microwave power sensor, the length and width of the membrane is 800 and 200 μm, and the height of the gap is 1.6 μm in order to obtain good sensitivity. Figure 2 shows a photo of the microwave frequency detector under testing. The process will be introduced in the following part of fabrication.

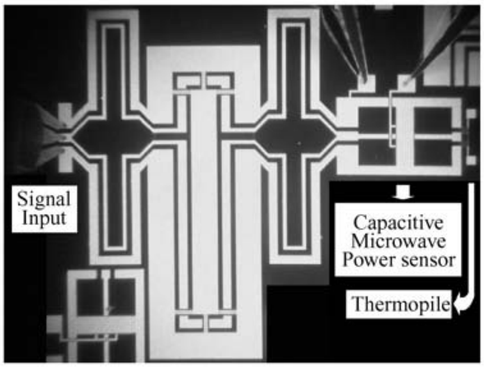

Fig. 2. Photo of the microwave frequency detector under testing.

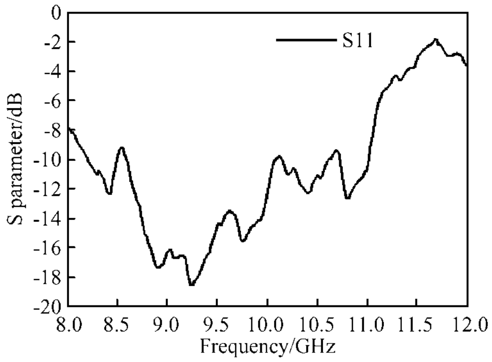

Fig. 3. S-parameter of the microwave frequency detector structure.

3. Fabrication

The fabrication of the microwave frequency detector is compatible with the GaAs MMIC process using Au surface micromachining. The thermopiles are made of Au and n^+ GaAs. The gold is made by sputtering of a 0.3 μm thick Au layer, and the n^+ GaAs is made of a 0.25 μm thick epitaxial layer. The CPW line is fabricated evaporating the 800/300/2200 Å Au/GeNi/Au layer. The dielectric Si_3N_4 layer 1000 Å is deposited. Then a 1.6 μm thick polyimide sacrificial layer is deposited, which determines the initial height of air gap. A 500/1500/300 Å Ti/Au/Ti seed layer is finally sputtered. To remove the top Ti layer, the membrane is electroplated of a 2 μm thick Au layer.

4. Results and discussion

S-parameters of the frequency detector are measured using an Agilent 8719ES network analyzer and a Cascade Microtech 1200 probe station over the frequency range at X-band (8–12 GHz) as shown in Fig. 2. Moreover, it can be seen that the return loss (S_{11}) decreases towards the center frequency in Fig. 3. The return loss is less than –1.909 dB over the frequency range from 8 to 12 GHz. The ripple obtained is measured, and it can be seen that the transmission loss decreases around 10 GHz. As the designed detector is based on the center frequency, the impedance mismatch and the losses always exist.

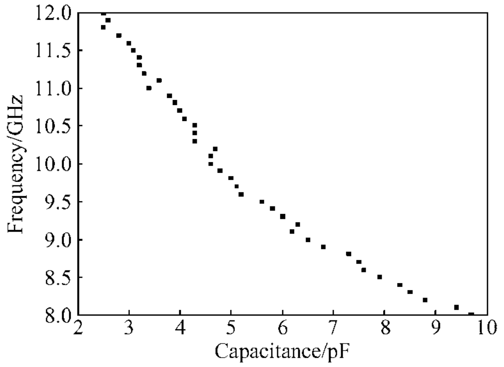

Fig. 4. Dependence of frequency and the measured capacitance under 17 dBm.

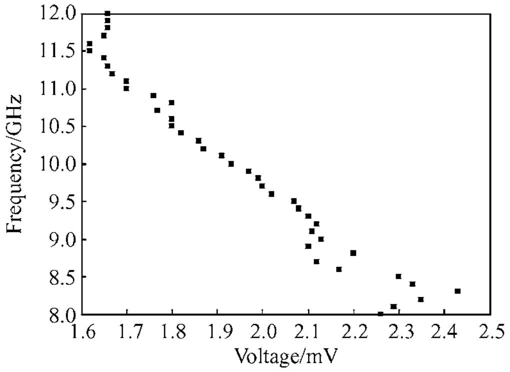

Fig. 5. Dependence of frequency and the measured voltage under 10 dBm.

Microwave frequency detection measurements with the sensor is realized with an Agilent E8257D PSG Analog Signal Generator and a Cascade Microtech 1200 probe station over the frequency range from 8 to 12 GHz. After passing through the microwave frequency detector, the capacitance between the sensing electrodes and the bridge is detected by the digital bridge (LW-2811c), or the output voltage of the thermopile is detected by the voltmeters (FLUKE 45). In this way, the characterization of the frequency of the microwave signal traveling through the detector and the movement of the bridge or the changes of the voltage can be obtained.

The measurement results of the detection by signals with different power over X-band are illustrated in Figs. 4 and 5, respectively. Figure 4 shows the measurement results of the frequency with the change of the capacitance. Microwave under 17 dBm at X-band is applied, and the values of the capacitance change are recorded. It is easily seen that continuous frequency at X-band exhibits linearity for the value of capacitance change, corresponding the figure-of-merit of 0.56 MHz/fF. The measured differential frequencies with the change of the voltage are showed in Fig. 5. Microwave under 10 dBm over X-band is applied at the input. The output voltage of the thermopile increases linearly and the sensitivity is better than 6.67 MHz/μV. Better characterization can be realized from 9 to 11 GHz around the center frequency. From Figs. 4 and 5, we can see the sensitivity of the two kinds of detection structures is not ideal. The reason is due to the ohmic losses of the CPW line, the decrease of the membrane height g_0 and the error of the CPW dimension caused by process. More precise detection and calibration circuits are now under further investigation.

5. Conclusion

In this paper, an MEMS microwave frequency detector based on CPW configuration has been proposed. Prior to the integration of the whole circuitry, the individual part is carefully designed and optimized. The detector has been designed and fabricated. The sensitivity is 0.56 MHz/fF under 17 dBm by the capacitive power sensor, and 6.67 MHz/μV under 10 dBm by the thermopile, respectively.

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