GaAs MMICs Using BCB Thin Film Layers for Automotive Radar and Wireless Communication Application

Yuji Iseki, Eiji Takagi, Naoko Ono, Junko Onomura, Keiichi Yamaguchi, Minoru Amano, Masayuki Sugiura*, Hiroshi Yamada, Yasushi Shizuki**, Takashi Togasaki***, Kazuhito Higuchi***, Kazuki Tateyama***

Corporate Research and Development Center, Toshiba Corporation
*Toshiba Corporation Semiconductor Company
**Toshiba Corporation Information and Industrial Systems & Services Company
***Corporate Manufacturing Engineering Center, Toshiba Corporation

1, Komukai Toshiba-cho
Saiwai-ku, Kawasaki 212-8582
Japan
Phone: +81-44-549-2280
Fax: +81-44-520-1806
e-mail: yuuji.iseki@toshiba.co.jp

Abstract

This paper describes MMIC miniaturization technology and Flip Chip assembly technology using solder bumps, which are the key technologies for low-cost millimeter wave systems. With MMIC miniaturization technology, a new transmission line structure using BCB thin films was proposed. A MMIC chip set was developed using the new structure and the conventional structures, and the superiority or inferiority was clarified. With MMIC Flip Chip assembly technology, the solder bump was formed by electroplating. Furthermore, assembly was carried out on a substrate, and, as a result of performing a reliability examination and scattering parameter acquisition, it was clarified that there was no problem with respect to the structure and the RF characteristics.

Key words:

Millimeter Wave, MMIC, BCB, Transmission Line Structure, Solder Bump, and Flip Chip.

1. Introduction

In view of the proliferation of multimedia, there has been increasing interest in the possibilities of using millimeter waves as a new electromagnetic wave resource. The millimeter wave is an electromagnetic wave of the 30-300 GHz frequency bandwidth wavelength of 1-10 mm. Communications in millimeter waves are characterized by high bit rate and large capacity transmissions, due to their wide frequency range. Also, using millimeter waves, precise measurements can be carried out due to their short wavelength. As far as devices are concerned, the extremely short wavelength property of millimeter waves is beneficial for manufacturing very small electrical circuits and components. Given these characteristics of millimeter waves, development of automotive radar, using 60 GHz and 76 GHz bands, and wireless LAN, using the 60 GHz band, has been pursued aggressively.

A low-cost packaging technology for a millimeter wave circuit will decide utilization of these millimeter wave systems. In order to produce a low-cost millimeter wave circuit, a planar circuit called microwave integrated circuit (MIC) or monolithic
microwave integrated circuit (MMIC) was employed for the millimeter wave circuit structure instead of the three-dimensional structure using metal waveguides. The MIC is constructed from a discrete chip formed an active device and dielectric substrates that the transmission lines or passive devices are formed, as shown in Figure 1(a). The MIC has an advantage with respect to electrical performance, since the highest performance chip and substrate can be selected and the circuit can be easily trimmed. However, the MIC assembly process is complex and costly.

Figure 1. Comparison of MIC and MMIC.

In the MMIC, passive elements and transmission lines are formed on the same semiconductor substrate on which the active elements have been formed, as shown in Figure 1(b). Although the MMIC is inferior with respect to performance, it is excellent in terms of miniaturization and mass production.

In this paper, the authors describe a newly developed MMIC chip set adopting benzo-cyclo-butene (BCB) thin film layers as insulating substrates on the GaAs substrate. Further, the researchers introduce Flip Chip technology using the PbSn solder bump. In a millimeter wave circuit, the assembly process influences production costs, in addition to the costs of the assembled components. Application of Flip Chip technology is expected to lead to lower assembly process costs.

2. Developed MMICs

2.1. Comparison of Transmission Line Structures

The chip area and the yield in the wafer process have contributed to the high cost of manufacturing GaAs MMICs since expensive epitaxial wafers are used in many cases. In MMIC, active elements and passive elements made of transmission lines are formed on one chip. Generally, the passive element area is larger than the active element area. Therefore, devising an optimum transmission line structure is the key to reducing MMIC chip area.

The transmission line structures generally used in MMICs are shown in Figure 2. The microstrip line (MSL) is simple composition and most widely used. A conductive layer is formed on the back MMIC as a ground plane, and a transmission line is formed on the MMIC surface. Since the library models currently prepared by computer aided design (CAD) tool are substantial, designing a MMIC is comparatively easy. However, a back process, such as wafer grinding or via-hole making, is necessary.

Figure 2. Conventional transmission line structures.

A coplanar waveguide (CPW) structure is formed only by the conductive layer of the MMIC substrate surface, therefore the backside process is unnecessary. However, it is difficult to design with high precision since layout flexibility is low and the CAD model library is very poor.

The thin film microstrip line (TFMSL) is a relatively new structure. In this structure, a back process is not necessary as in the case of the CPW. Furthermore, the transmission line can be made compact since the resin film can be made thin. However, a narrow transmission line may cause line resistance high and degrade MMIC performance.

Figure 3 shows the new transmission line structure for the MMIC. This structure combines the CPW and TFMSL, and enables a transmission line to be used properly, according to the purpose of the line. In other words, proper use of the CPW for the transmission line respecting which it is desired that transmission line loss be as small as possible, and proper use of the TFMSL for the circuit for which miniaturization is more important than transmission line loss. Moreover, since a stub using the TFMSL can be set on any desired part of the CPW transmission line, in any case, the design flexibility is increased. How-
ever, it is not necessarily the optimum structure for all MMICs. MMICs were actually developed and the validity was checked.

Figure 3. New transmission line structure.

2.2. Developed MMICs

The authors developed three kinds of MMICs, amplifier (AMP), voltage controlled oscillator (VCO), and mixer (MIX), for the 60 GHz band. These MMICs utilized a 0.1 µm T-gate GaAs pseudomorphic-high electron mobility transistor (p-HEMT). For the thin film dielectric material, BCB was used. BCB is similarly used in many cases as an insulator for thin film multilayer substrates with polyimide (PI). Table 1 shows the electrical and thermal characteristics of BCB and polyimide. Thus, BCB is superior to polyimide in these attributes.

(a) AMP

The authors also designed and fabricated two different four-stage amplifier MMICs, as shown in Figure 4. One is a conventional type which used only the CPW structure. The other is a MMIC with the proposed structure which used both the CPW for millimeter wave signal lines and the TFMSL for bias circuits. The MMIC with the proposed structure was 22.5% smaller than the conventional one. Figure 5 shows the measured gain of the AMP MMICs. The MMIC with the new structure achieved high gain over wide frequency range, whereas the conventional type did not. This is attributed to the fact that the proposed structure can set a stub nearer the HEMT device than the CPW structure.

Table 1. Electrical and thermal characteristics of BCB and PI.

<table>
<thead>
<tr>
<th>Item</th>
<th>BCB</th>
<th>PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative dielectric constant</td>
<td>2.7 @1 MHz</td>
<td>3.3 @1 kHz</td>
</tr>
<tr>
<td>Dielectric loss tangent</td>
<td>0.0008 @1 MHz</td>
<td>0.002 @1 kHz</td>
</tr>
<tr>
<td>Curing temperature</td>
<td>210-250 °C</td>
<td>400 °C</td>
</tr>
<tr>
<td>Water uptake</td>
<td>0.08 %</td>
<td>2.1 %</td>
</tr>
</tbody>
</table>

(b) VCO

The VCO chip was designed and fabricated on the basis of the CPW and the TFMSL. Although the TFMSL type MMIC was smaller than the CPW type MMIC shown in Figure 6, the TFMSL-type MMIC did not oscillate. The reason is that the characteristics of the HEMT, such as cut-off frequency \( (f_T) \), Maximum Stable Gain (MSG) and capacitance between the gate and the drain \( (C_{gd}) \), declined due to the covering of the HEMT with BCB. Figure 7 shows the measured output signal spectrum of the CPW-type MMIC. At 60.5 GHz, the output power was -1 dBm, and the 1-MHz off-carrier phase noise was -89 dBc/Hz.
with a modulation sensitivity of 300 MHz/V.

Figure 6. GHz band VCO with CPW structure.

![GHz band VCO with CPW structure.](image)

\[f = 60.5 \text{ GHz}, 10 \text{ MHz/div}\]

Figure 7. Output signal spectrum.

(c) MIX

Figure 8 shows the developed single-ended drain MIX utilizing the TFMSL structure\(^5\). An RF signal and an LO signal were applied to the HEMT with TFMSL. An IF signal was taken from the HEMT via a TFMSL low pass filter. The bias circuit were formed beneath the ground plane of the TFMSL. The measured conversion gain versus local power for an RF frequency of 62.5 GHz, and a local signal frequency of 63 GHz, is given in Figure 9. Zero conversion gain was achieved with a low local input of 0 dBm.

![60 GHz band MIX with TFMSL structure.](image)

As mentioned above, the superiority or inferiority of transmission line structures was clarified. Since a multi-stage AMP and a MIX have many passive components, the effect of their miniaturization using thin film is large. In particular, as with the AMP MMIC, the MMIC with the proposed transmission line structure achieved higher gain than the conventional type over wide frequency range. However, in the case of the VCO, the desired performance may not be obtained when a BCB film is used. It is necessary to choose transmission line structure according to the function of the MMIC.

3. PbSn Solder Bump

3.1. Structure

Currently, almost all the bump material developed for millimeter wave MMIC is Au or AuSn\(^2\). This is due to the fact that the affinity between these materials and GaAs chip fabrication process is good. However, these materials are inconvenient in several respects regarding mass production. That is, the assembly process temperature is high and the assembly substrate is restricted to a ceramic substrate. On the other hand, the PbSn solder bump is already used for mass production with Si LSIs\(^8\). Solder has several merits, such as, the high self-align effect, the low assembly process temperature, and a resin can be chosen as an assembly substrate material. Therefore, if a millimeter wave system were mass-produced, solder bumps would be advantageous in terms of production cost. The weak point of PbSn is poor affinity with the existing GaAs wafer process. Au is generally used for the conductor in GaAs MMICs. Since PbSn solder is apt to spread in Au when PbSn and Au contact directly, the role of the barrier metal formed between Au and PbSn becomes much more important. The bump structure adopted is shown in Figure 10. The copper layer under the PbSn solder is the barrier metal layer. It was formed by the electroplating process as with PbSn, and sufficient barrier-metal intensity was secured.
Figure 10. PbSn solder bump structure.

Figure 11 shows SEM micrographs of fabricated bumps after the reflow process. There are three kinds of bump pitch: 50, 100, and 150 µm. The bump height is about 35 µm for 50 µm pitch, about 50 µm for 100 µm pitch, and 55 µm for 150 µm pitch. The die share strength was more than 50 MPa. This is sufficient value for high reliability interconnection. Furthermore, the interconnection resistance per bump in a 150°C high-temperature storage test is shown in Figure 12. The connection resistance after 1000 hours was less than 20 mΩ.

3.2. RF Characteristics

The fabricated chip was assembled on the substrate and the scattering parameter was measured before and after underfilling. Figure 13 shows the measured sample which is composed of the chip with solder bumps and the Cu/BCB thin film multilayer substrate. Figure 14 shows the SEM micrograph of the assembled sample. The chip size is 3 mm x 1.6 mm, and the bump pitch is 150 µm. The transmission line structure on the TEG chip is a CPW, and that on the assembly substrate is a TFMSL. The characteristic impedance of each transmission line was 50 Ω in the design. Since the reference planes were set at the middle of the TFMSL using the through-reflect-line calibration method, the frequency characteristics shown in Figure 15 include the characteristics of two sets of 685-µm long TFMSLs on the assembly substrate, two sets of solder bumps, and a 1440-µm long CPW on the GaAs chip. It was found that there was no unnecessary resonance and the signal from the DC to a millimeter wave passed without any problem.
4. Conclusion

A millimeter wave MMIC chip set with various transmission line structures was developed and evaluated. As a result, it was found that a BCB thin film layer was effective in the miniaturization of an MMIC chip, and it was desirable to choose transmission line structure according to the purpose of the MMIC. Moreover, the authors have developed and evaluated the PbSn solder bump on a GaAs MMIC. The mechanical and electrical characteristics of the fabricated solder bump were confirmed to be sufficient.

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References