In response to the requests received since 2006 from overseas Tier 1 manufacturers (primary corporations that directly supply parts to automobile manufacturers), Mitsubishi Electric developed the MGF4941CL and the MGF4841CL discrete high electron mobility transistor (HEMT) amplifiers employing GaAs, and commenced their mass production in 2014. These amplifiers constitute the core of the circuits in the transmitting and receiving section of the 24 GHz band short-distance-detection radar sensor module designed to accurately measure the distance and relative velocity between an automobile and an object in the vicinity. This paper presents an overview of the process leading to the commercialization of these discrete HEMT amplifiers, which are intended to be mounted in automobiles.

1. Introduction

In the field of vehicle-mounted devices, millimeter-wave radar sensor modules that accurately measure the distance, relative velocity, and direction between one’s own automobile and a vehicle or object in the vicinity are widely employed as monitoring sensors in systems such as adaptive cruise control (ACC) and pre-collision safety systems, which are required to be highly weather resistant. The millimeter-wave radar sensors are classified into the 77 GHz band millimeter-wave radar, which exhibits its true performance in long-range (50–200 m) detection, and is used mainly in long range radars, and the 24 GHz band quasi-millimeter-wave radar, which is used mainly as SRR for short-range (up to 50 m) detection. SRR is used mainly to reduce the risk of a collision through the detection of vehicles on the rear and front lateral sides.

In the European market, the 24 GHz band is gradually being replaced by the 77 GHz band (79 GHz in the case of short-range detection) to comply with regulations. However, in the US as well as in China and other emerging nations, increasing use of the 24 GHz band is also expected in the future, partly because of the relatively low cost.

In contrast to 77 GHz, which is the main frequency band used by monolithic microwave integrated circuits (MMIC), long-wavelength 24 GHz band radar modules make it possible to use discrete semiconductors in function devices, such as an amplifier, by building a circuit on the substrate side. Particularly in the case of a receiving stage amplifying device, the low-noise performance of HEMT amplifiers is prominent. Compared to CMOS or SiGe amplifiers with superior integration, HEMT amplifiers are needed to a certain extent in the market. Since 2006, Mitsubishi Electric has also been promoting the development of products related to receiving stage amplifiers that are to be installed in 24 GHz band radar modules. In 2012, we commenced mass production and shipment of these modules to coincide with the commercialization of customers’ modules. During the development stage, we developed the same factors as those of products intended for DBS in order to utilize existing resources. As a result, we succeeded in minimizing development costs, and currently supply products that offer low cost and high performance (low-noise performance). Also, when expanding the number of models in this group of vehicle-mounted products, it is possible to complete the performance/reliability validation in a relatively short time (within six months), and promptly respond to customer demand, by using common components with verified performance and reliability for semiconductor chips, packages, and other parts during the assembly process.

As a result of these efforts, since the end of 2014 we have manufactured and supplied to customers mainly in Europe a total of nearly 30 million discrete HEMT amplifying devices for mounting in vehicles.

2. Discrete HEMT Amplifiers for Mounting in Vehicles

Figure 1 shows the exterior of the package of the MGF4941CL model HEMT amplifier currently being produced, and Table 1 shows the specifications of the product characteristics (the MGF4941CL and the MGF4841CL use the same package). Based on the discrete HEMT amplifier product, which has a hollow plastic package construction developed for DBS, we secured the necessary reliability for vehicle mounting, and prepared an inspection setup, and to date we have commercialized the excellent low-noise model HEMT amplifier MGF4941CL and also the higher output model HEMT amplifier MGF4841CL. The following sections describe the items that were considered when designing the product for mounting in a vehicle.
Fig. 1 Package photograph of MGF4941CL HEMT amplifier for automotive application

Table 1 Specification of MGF4941CL/MGF4841CL HEMT amplifier for automotive application

<table>
<thead>
<tr>
<th>Type No.</th>
<th>Test item</th>
<th>Test Condition</th>
<th>Drain current</th>
<th>Gate to drain breakdown voltage</th>
<th>Gate to source cut-off voltage</th>
<th>Noise figure</th>
<th>Associated gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGF4941CL</td>
<td>VDS=1.5V, VGS=0V</td>
<td>-</td>
<td>25mA to 45mA</td>
<td>IG=−10μA</td>
<td>VDS=1.5V, IDS=500μA</td>
<td>VDS=1.5V, VGS=0V</td>
<td>f=25.2GHz, Ta=25°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>−3V</td>
<td>−1.5V to −0.1V</td>
<td>2.4dB</td>
<td>12.0dBm</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>MGF4841CL</td>
<td>VDS=2.5V, VGS=0V</td>
<td>-</td>
<td>30mA to 80mA</td>
<td>IG=−10μA</td>
<td>VDS=2.5V, IDS=500μA</td>
<td>VDS=1.5V, VGS=0V</td>
<td>f=24.3GHz, Ta=25°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>−4V</td>
<td>−2.0V to −0.1V</td>
<td>12.0dBm</td>
<td>8.5dB</td>
</tr>
</tbody>
</table>

2.1 Production part approval process
First, the production part approval process (PPAP) concerning parts to be mounted in an automobile during development of the automobile, which are stipulated by the quality management system requirements for installation of automotive-related products ISO/TS 16949: 2009 (former QS-9000: 1998), is described. The process includes a product design record agreed upon with the customer, product standard, design (process) failure mode and effect analysis (FMEA), process flow, control plan, reliability test, trial manufacture results, and process ability survey, and must be disclosed to the customer and also be approved by the customer in advance. Regarding Tier 1 customers in Europe, it is necessary to carry out in parallel with the PPAP a self-audit based on the VDA6.3(3) standard auditing tool in the automobile industry in Germany. In addition, manufacturers are required by customers to undergo an audit, and all of their production lines, including factories related to the production, are required to have at least a certain level of competence. Based on the foregoing, Mitsubishi Electric undergoes a production line audit from multiple customers with whom we currently have dealings. Also, we have received approval from these customers for our wafer production plant (high-frequency optical device production plant), and for one factory of an affiliated company that is in charge of assembling and testing the package.

2.2 Reliability testing of discrete parts to be used in vehicles, and an example of securing reliability in the wafer process
Based on AEC-Q101, which is a test standard for general discrete semiconductor components intended for mounting in automobiles in Europe, we carry out reliability tests for validating the temperature resistance, humidity resistance, and ESD resistance characteristics, confirm that the devices maintain sufficient reliability to withstand the tests, and then submit a report to each of the main customers according to the PPAP, and receive their approval. We thus promote these devices as “AEC-Q101 approved.” At present, we have received AEC-Q101 approval for five models of discrete HEMT amplifier products including the abovementioned two models.

Generally, when manufacturing an HEMT amplifier device, a non-hermetic package, such as a plastic, is used in order to reduce the cost, which causes a significant issue with the humidity resistance of the semiconductor chip and its reliability. When developing this product for vehicle mounting, various means were used in order to meet the far more stringent reliability (humidity resistance) standard than that for DBS use. An example follows (see Fig. 2 for an outline of the process). During the process in which the protective
film is formed after the gate electrode of the HEMT transistor is formed, plasma processing is employed during the cleaning process that is implemented immediately before forming the protective film to remove traces of the residue of the resist layer and also the naturally oxidized layer from the surface of the semiconductor near the gate. As a result, we succeeded in improving the adhesion of the semiconductor layer and the protective film, thus suppressing the fluctuation of properties due to deterioration of the GaAs surface in a high-temperature, high-humidity environment.

2.3 Reduction of initial failure rate by means of a total S parameter inspection

To allow for a product group that we have already been shipping for the DBS market to be shipped as vehicle-mounted products, which are required to have higher quality (initial failure rate less than 100 ppm), normally it is necessary to study methods of carrying out a total inspection of the high-frequency characteristics (noise figure [NF] in the case of a low-noise amplifier). However, as the high-frequency characteristics in the 24 GHz band are readily affected by the contact between the device and the measuring jig, it is extremely difficult to carry out a test in a short time, so this method is impractical for a total inspection of a large quantity of products. Accordingly, as shown in Fig. 3, we focused on the correlation between the drain current (IDSS) that can be verified through a simple DC (DC electric characteristics) measurement, and the NF, and then set up a standard using IDSS. Next, to verify the frequency characteristics, we proposed an inspection method that uses a part averaging test limit(4) for the total inspection standard for S11, which has the closest correlation with the NF among the S parameters. We will be implementing this inspection method subject to the customer’s approval. Figure 4 shows the method for rejecting a product with an S11 parameter that deviates from the correct distribution (in actual fact, there is a high probability of the NF also deviating from the correct distribution) that cannot be completely rejected by the settings of an ordinary inspection standard alone, when carrying out a total S parameter inspection.
inspection on a product in the vicinity of $\text{IDSS} = 35 \text{ mA}$ as shown in Fig. 3. By using this method within the entire IDSS range, it is possible to select an NF (Fig. 3) in the standard (correct distribution).

For the actual product inspection process, we developed a unique system for implementing a total S parameter inspection that has an inspection averaging test function and a statistical bin limit\(^{(5)}\) function, and we are using it for mass production.

3. Conclusion

We commenced development of the low-noise MGF4941CL HEMT amplifier and the medium-output MGF4841CL HEMT amplifier intended for mounting in a vehicle, and realized mass production via the PPAP and the AEC-Q101 test standard covering discrete parts for mounting in vehicles, which the devices passed. We will use the findings obtained from the development of these products, and will strive to accelerate the development of products for new markets (V2X).

References

(1) AEC-Q101 Rev.C STRESS TEST QUALIFICATION FOR AUTOMOTIVE GRADE DISCRETE SEMICONDUCTORS, Automotive Electronics Council (2005)
(4) AEC-Q001 Rev.D GUIDELINES FOR PART AVERAGING TESTING, Automotive Electronics Council (2011)
(5) AEC-Q002 Rev.B GUIDELINES FOR STATISTICAL YIELD ANALYSIS, Automotive Electronics Council (2012)