High-Reliability Deep Submicron GaAs Pseudomorphic HEMT MMIC Amplifiers

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Abstract

High-reliability performance of a Q-band MMIC amplifier fabricated using TRW's 0.1 μm production AlGaAs/GaAs HEMT process technology is reported. Operating at an accelerated life test conditions of Vds=4.2V and Ids=150mA/mm, two-stage balanced amplifiers were lifetested at three-temperatures (T_a=255°C, T_a=270°C, and T_a=285°C) in air ambient. The activation energy (Ea) is as high as 1.7 eV, achieving a projected median-time-to-failure (MTF) of $6x10^9$ hours at a 125°C junction temperature. MTF was determined by a 3T constant current stress using | ΔS21 | > 1.0 dB as the failure criteria. This is the first report of high reliability 0.1 μm GaAs pseudomorphic HEMT MMICs based on small-signal microwave characteristics of HEMT MMIC amplifiers lifetested at high junction temperatures. This result demonstrates a robust 0.1 μm GaAs PHEMT technology highly immune to the stress effects of high electric field and high temperature operation. The high reliability of 0.1 μm GaAs HEMT technology is significant for the both commercial and military applications in the millimeter wave frequency band.

INTRODUCTION

We have developed a highly robust both 0.1 μm and 0.15 μm GaAs HEMT MMIC technology that has demonstrated superior millimeter wave performance to meet the strong demand of present and future commercial and military electronic systems (1-5). With GaAs HEMT becoming a preferred technology for system performance improvement or the next generation system design, the demonstration of a robust technology for providing reliable, high performance MMICs at low cost and high yield to both the space/defense and commercial markets is essential. However, while the published data of GaAs HEMT reliability has been mostly focused on 0.15 μm GaAs HEMTs technology(6), few investigated the lifetest of 0.1 μm GaAs HEMT MMIC level which allows the reliability assessment on GaAs HEMT devices, passive element, via hole integrity, thin film resistors metal and interconnect. In addition, most of published reliability data has been focused on the discrete device only [7-9]. Accordingly, it is important to have available reliability information of 0.1 μm GaAs pseudomorphic HEMT MMIC amplifiers to assure the success of GaAs MMICs insertion for both commercial and military applications in the millimeter wave frequency band.

In this paper, high reliability non-hermetic 0.1 μm GaAs pseudomorphic HEMT MMIC amplifiers was demonstrated. The results benefit both microwave and wireless communities by demonstrating a reliable and robust GaAs pseudomorphic HEMT technology, a critical factor in widespread acceptance of GaAs pseudomorphic HEMT MMIC amplifiers for microwave & wireless applications.

PROCESS TECHNOLOGY

TRW's standard 3 inch GaAs pseudomorphic HEMT production process was grown on semi-insulating substrates by solid source molecular beam epitaxy (MBE). The channel carriers are supplied by two silicon delta doping layers ($4.7x\ 10^{12}$ cm^{-2} and $1.0x10^{12}$ cm^{-2}). The epitaxial layers with 2-dimensional electron gas (2-DEG) carrier density of $3.56x10^{12}cm^{-2}$ and Hall mobility of 4,600 cm^2/V-s at room temperature. While $Al_{0.25}Ga_{0.75}As$ with a thickness of 500Å is used as the Schottky barrier layer, $In_{0.22}Ga_{0.78}As$ with a thickness of 140 Å is used as the channel layer. Heavily-doped GaAs layer is used to facilitate the ohmic formation.

Ni/AuGe/Ag/Au and refractory Ti/Pt/Au are used for the drain and source ohmic metal and gate contact, respectively. A 0.1 μm T-gate shown in Figure 1 was patterned by two layers (PMMA, P(MMA-MAA)) electron beam lithography. The gate recess profile was controlled by wet-etch process. After the gate definition, the device was fully passivated by 750 Å Si_3N_4 to minimize the feedback capacitance and other parasitic capacitance.

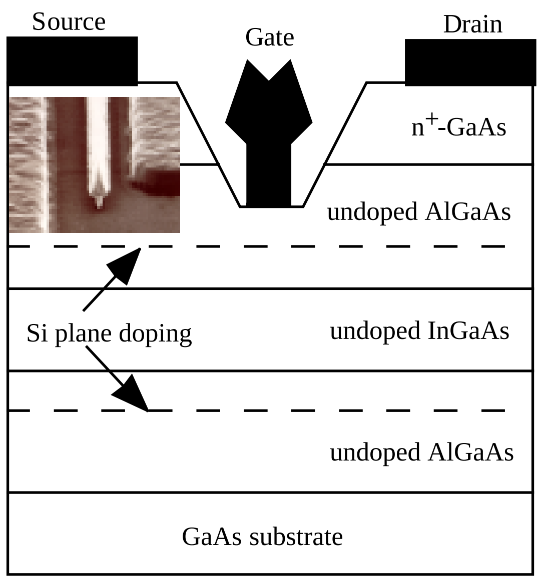

Fig.1: Cross section of an AlGaAs/InGaAs power HEMT (Insert: 0.1 μm T-gate).

With this technology, we have achieved excellent wafer to wafer repeatability over a hundred recently fabricated 0.1 μm GaAs HEMT wafers, including very tight control of both gate length (Lg=0.0933+/-0.011 μm) and recess size (W=0.2858+/- 0.0625 μm). Vp control is also pretty tight with a typical standard deviation of 80 mV. The transconductance is greater than 600 mS/mm, cutoff frequency > 120 GHz at 2V drain bias and maximum oscillation frequency greater than 200 GHz.

STANDARD EVALUATION CIRCUIT

A Q-band balanced MMIC amplifier of ALH225C operating in the frequency range of 35 to 46 GHz MMICs with a typical gain of 15 dB was designed for the reliability evaluation of 0.1 μm GaAs pseudomorphic HEMT. ALH225C is a two-staged balanced amplifier with a total agte periphery of 240 μm. During the lifetest, ALH225C was biased at Vd=4.2V and Ids= 150 mA/mm. A micrograph of a ALH225C is shown in Figure 2.

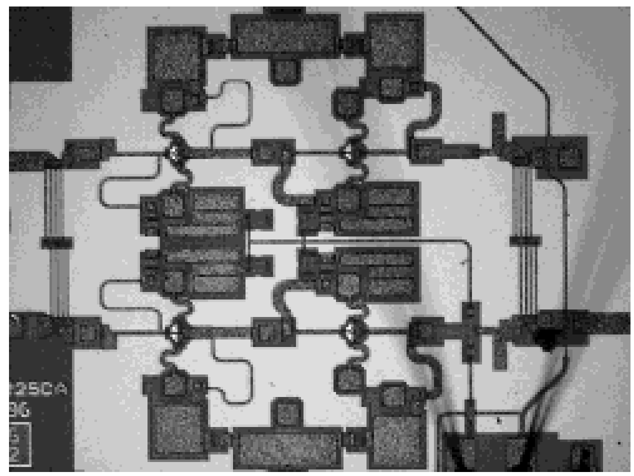

Fig.2: Micrograph of a Q band balanced amplifier operating over 35-46 GHz. Chip size is 2.8 mm x 1.75 mm.

Three Temperature Lifetest

Reliability evaluation of 0.1 μm GaAs pseudomorphic HEMT at TRW is determined by three temperature constant current stress where aging of discrete passive and active components is accelerated at elevated temperatures under full DC bias. Three-temperature constant lifetest is a standard procedure in industry for reliability assessment and is used to determine failure cumulative distribution, median-time-to-failure (MTF), and activation energy (Ea) based on the Arrehenius plot.

A total 102 MMICs were randomly selected across 4 wafers, 2 lots for three temperature reliability evaluation. All the selected MMICs passed the on-wafer DC, RF (S-parameter and noise figure) and visual screening requirements. Following the assembly, and prior to three-temperature lifetest, all parts were burned in at 150°C for 48 hours in air ambient by biasing at Vds=2.5V, Ids=125 mA/mm. The burn-in process would screen out the failure from the infant mortality. In addition, step stress was used to determine the suitable temperature for 3T lifetest. Based on the result of step stress (10), the ambient temperature selected for 3T lifetest was 255°C, 270°C, and 285°C with an estimated ΔTj=45°C. This results in the estimated channel temperature of 300°C, 315°C, and 330°C.

During the lifetest, samples were cooled down to room temperature for S-parameter and complete DC (Gm, Ids, Ig, ideality factor, Schottky barrier height) measurement. As shown in Fig.3, the S21 change of lifetest at $T_{ambient}$=285°C was plotted as a function of stress elapsed time. For this lifetest, the failure criterion was determined as a 1.0 dB degradation of S21 gain at 40 GHz compared to the pre-lifetest level. From this plot, the log normal distribution at $T_{ambient}$=285°C could be determined. The similar measurement was applied onto the lifetest of 255°C and 270°C in order to obtain the log normal distribution at $T_{ambient}$=255°C and 270°C.

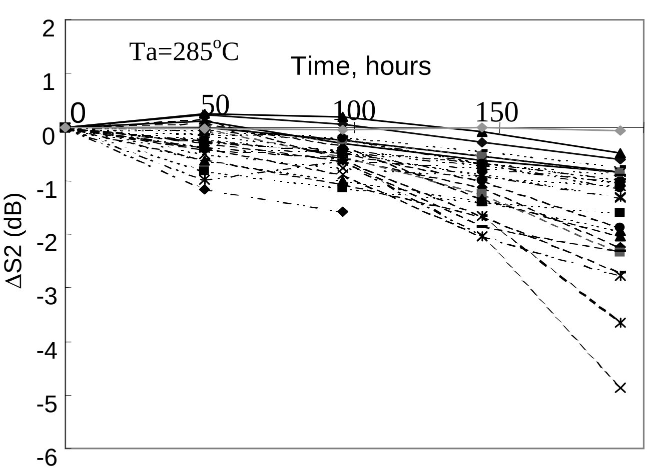

Fig.3: Room temperature S21 changes of a Q-band MMIC amplifiers subjected to lifetest at $T_{ambient}$=285°C.

In addition to characterizing the microwave performance, the complete DC measurement was also applied to help understand the possible degradation mechanism involved. As shown in Fig.4, Ids decreases during the lifetest at 285°C. The decrease in Ids is accompanied by a shift in Gm toward the more positive Vg without affecting the peak Gm, followed by a reduction in peak Gm. This is characteristic of gate metal sinking effect during lifetesting. Lifetest at both 255°C and 270°C show the similar phenomena. Accordingly, it is believed that S21 change is induced by the Gm reduction during the high temperature lifetest.

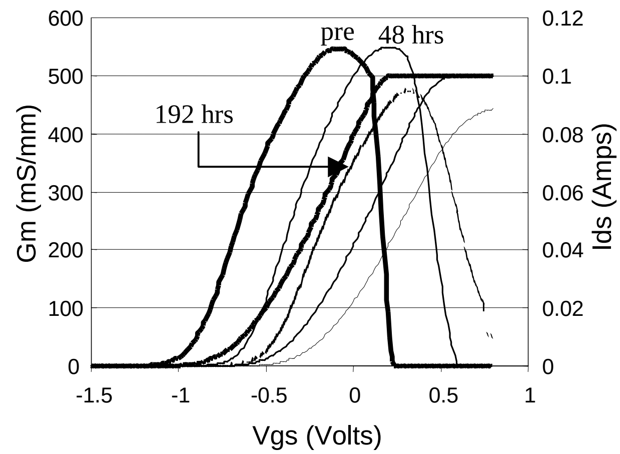

Fig.4. Gm and Ids changes of a Q-band MMIC amplifiers subjected to lifetest at $T_{ambient}$=285°C.

LIFETEST RESULTS

Lifetest failures exhibit a log-normal characteristics with temperature-independent log-standard deviation (sigma). The lifetest failure distribution is plotted on a log-normal scale shown in Fig.5. Measured sigma was approximately 0.45. The median failure times from Fig. 5 are plotted in an Arrhenius plot in Fig. 6. The Arrhenius model projects a MTF of 6×10^9 hours at a 125°C junction temperature with an Ea=1.7 eV. This result shows state-of-the-art reliability on 0.1 μm GaAs HEMT MMIC amplifiers stressed at high Tj in air ambient.

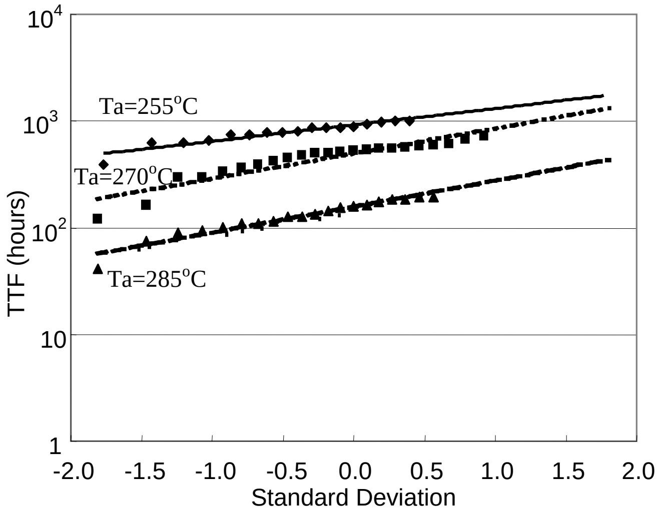

Fig.5: Failure distribution of 3 T lifetest plotted on a log-normal scale. Ta is the ambient temperature.

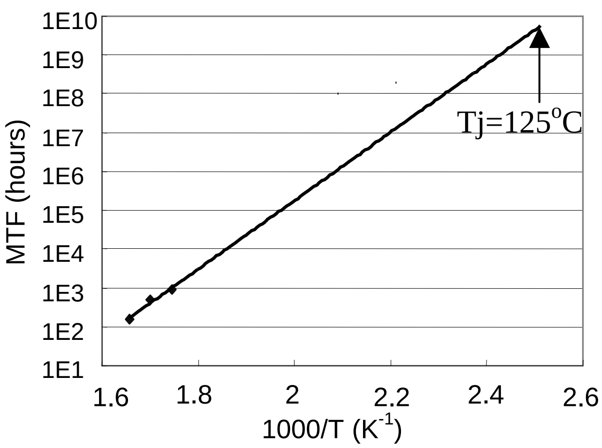

Fig.6: Arrhenius plot of 0.1 μm HEMT MMIC amplifiers subjected to 3T lifetest at 255°C, 270°C, and 285°C.

CONCLUSION

High reliability performance of a Q-band MMIC amplifier fabricated using 0.1 μm GaAs pseudomorphic HEMT 3” production process technology is demonstrated by lifetesting MMICs in air ambient. The activation energy (Ea) is 1.7 eV, achieving a projected median-time-to-failure (MTF) of $6x10^9$ hours at T_j= 125°C. This is the state-of-art of reliability results on 0.1 μm GaAs HEMT based on microwave performance failure of MMIC amplifiers.

REFERENCES

[1]. R. Lai, M. Nishimoto, Y.Hwang, M. Miedenbender, B. Kasody, C. Geiger, Y.C. Chen and G. Zell, “A High Efficiency 0.15 μm 2-mil Thick InGaAs/AlGaAs/GaAs V-and Power HET MMIC,” *18th Annual IEEE GaAs IC Symposium Digest*, pp. 225-227, 1996.

[2]. M. K. Siddiqui, A. K. Sharma, L.G. Callejo, C.H. Chen, K. Tan, and H.C. Yen, “A High Power and High Efficiency Power Amplifier for Local Multipoint Distribution Service,” *1996 IEEE MTT-S Symposium, pp.701-704*.

[3]. M. K. Siddiqui, A. K. Sharma, L.G. Callejo, and Richard Lai, “A High-Power and High-Efficiency Monolithic Power Amplifier at 28 GHz for LMDS Applications,” *Trans. on Microwave Theory and Techniques, Vol.46, , pp.22261-2232, 1998*.

[4]. D. L. Ingram, D.I. Stones, T.W. Huang, M. Nishimoto, H. Wang, M. Siddiqui, D. Tamura, J. Elliott, R. Lai, M. Miedenbender, H.C. Yen, and B. Allen, “A 6 Watt Ka-band MMIC Power Module using MMIC Power Amplifier,” *1997 IEEE Int. Microwave Symposium, pp.1183-1186*.

[5]. M. V. Aust, B. Allen, G.S. Dow, R. Kasody, G. Luong, M. Biedenbender, and K. Tan, “A Ka-band HEMT MMIC 1W Power Amplifier,” *1993 IEEE MTT-S Symposium, pp.1343-1346*.

[6] D. Leung, Y.C. Chou, C.S. Wu, R. Kono, R. Lai, M. Hoppe and D.C. Streit, “ High Reliability Non-Hermetic 0.15 μm GaAs Pseudomorphic HEMT MMIC Amplifiers”, *RF Integrated Circuits Symposium Proceedings, Anaheim, CA, pp. 261-267, 1999.*

[7]. Y.C. Chou, G.P. Li, Y.C. Chen, R. Lai, and D.C. Streit, “ Reliability and Alleviation of Premature On-State Avalanche Breakdown in Deep Submicron Power PHEMT’s,” *Proceeding of 35th IEEE International Reliability Physics Symposium, Denver, CO, pp.261-267, 1997.*

[8]. Z. Y. Wang, J.Y. Qian, L.J. Cheng, G.P. Li, Y.C. Chou, R. Lai, and D.C. Streit, “ Deep Submicron PHEMTs Characterization with Spectrally Resolved Carrier Recombination Imaging,” *Proceedings of 1998 IEEE International Electron Device Meeting, San Francisco.*

[9]. C. Tedesco, C. Canali, F. Magistrali, A. Paccagnella, and E. Zanoni, “ Hot-electron induced degradation in AlGaAs/GaAs HEMT’s,” *Microelectronic Engineering, Vol.19, pp.405-408, 1992.*

[10]. D. Leung, Y.C. Chou, C.S. Wu, R. Kono,J. Scarpulla, R. Lai, M. Hoppe and D.C. Streit, “Reliability Testing of 0.1 μm GaAs Pseudomorphic HEMT MMIC Amplifiers”, *GaAs Reliability Workshop Digest, Monterey, CA, pp. 79-80, 1999.*