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An InP-Based HEMT and HBT MMIC Production Line

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Abstract

We report the development of an InP-based monolithic microwave integrated circuit production line to provide InP HEMT and InP HBT MMICs for both government and commercial applications. This three-inch fabrication facility was originally developed to produce high-performance InP HEMT and InP HBT MMICs specifically designed for government applications. Recent examples of performance capability include InP HEMT low-noise MMIC amplifiers with 12 dB gain at 155 Ghz, and the first fundamental frequency 94 Ghz HBT oscillator. However, InP-based heterojunction devices also provide specific advantages for some high-volume commercial applications. We present here the production and performance results of InP HEMT and HBT MMICs for governmnent and commercial applications.

I. Introduction

Compared to GaAs-based monolithic microwave integrated circuits (MMICs), InP-based MMICs offer significant advantages for many government and commercial systems. These advantages include better noise figure, lower DC power consumption, improved frequency performance, and higher linearity. TRW has developed an InP-based MMIC fabrication line to achieve volume production of advanced HEMT and HBT InP-based integrated circuits.

InP-based HEMT and HBT devices have been reported with outstanding discrete device performance for a number of years. [1,2,3,4], but these devices have been slow to make the transistion from research to production. One reason for this delay is that discrete devices no longer play an important role in most systems. MMICs are used rather than discrete devices to achieve significant savings in system size and power budgets. InP-based MMICs have not until recently reached the level of maturity that allows high-volume production.

We report here the development of a high-volume InP-based MMIC production line that follows the flexible manufacturing approach first used by TRW for GaAs-based MMIC production. InP-based HEMT and HBT devices and integrated circuits have been in development at TRW for over 10 years. The material and process uniformity and reproducibility have now reached a level of maturity that allows the performance advantages relative to GaAs based MMICs to be fully realized.

II. Background

We describe here the wafer manufacturing aspects of InP-based HEMT and HBT MMICs. Our approach has been to transition two-inch development processes to three-inch production while transforming the fabrication facility from a research laboratory to a high-volume manufacturing line. This transition from R&D to production takes advantage of the greater than fifteen years of experience at TRW in GaAs MMIC production and process transfers.

The two key aspects of this transition are to utilize common processes wherever possible to reduce the overall number of distinct process steps, and to utilize statistical process control to drive process control and improvement. The modular approach to processing both HEMTs and HBTs in the same process line yields efficiency and flexibility. The throughput of specific process steps is increased, providing improved process stability, easier process maintenance, and modular expansion capability.

II. Device Profile Design

Fig. 1 shows a cross section of TRW's InAlAs-InGaAs-InP HBT device structure. As illustrated, this vertical epitaxy structure is compatible with the monolithic integration of high performance InGaAs Schottky diodes and p-i-n photodetectors without requiring additional epitaxial regrowth.

The InAlAs-InGaAs-InP HBT device profile is grown by molecular beam epitaxy on semi-insulating 3-inch InP substrates. Be and Si are used as p-type and n-type

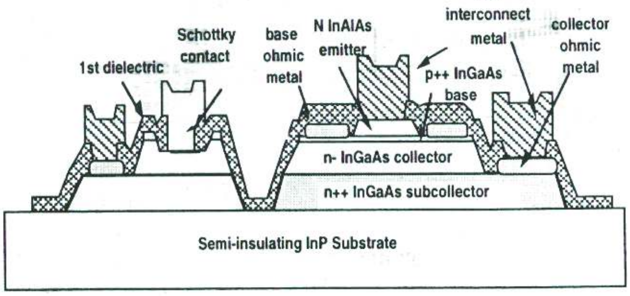

Fig. 1. InGaAs-InAlAs-InP production HBT profile.

dopants. The emitter uses an 80 nm n^+ InGaAs contact layer which is highly doped to obtain low emitter contact resistance. The n-type emitter region is 1200Å thick and doped to 5×10^{17} cm^{-3}. The base-emitter junction is compositionally graded from InGaAs to InAlAs to form HBTs with repeatable beta and low V_{be} characteristics. The base-collector epitaxial structure consists of a base thickness of 80 nm uniformly doped to 3×10^{19} cm^{-3}, a 700 nm thick n-type collector lightly doped to 1×10^{16} cm^{-3}, and an n^+ subcollector doped to 1×10^{19} cm^{-3}. The DC current gain beta across the wafers is ~20 at a collector current density of $Jc = 40$ kA cm^{-2}. The breakdown voltage BVceo is 8V and the BVcbo is 13V.

Fig. 2 shows noncontact photoreflectance spectra of representative two-inch and three-inch InP HBT epitaxial material prior to processing. The low-energy oscillations are associated with the InGaAs base-collector junction. The higher energy oscillations are associated with the base-emitter InGaAs-InAlAs heterojunction. We use photoreflectance of InP-based HBTs for the same reason as for GaAs-based HBTs [5]. The similiarity between the two-inch and three-inch spectra indicates accurate profile reproduction for both substrate types.

Fig. 3 shows a cross section of the InAlAs-InGaAs-InP HEMT epitaxial structure. The channel is 15 nm pseudomorphic InGaAs, 0.6 mole fraction InAs.

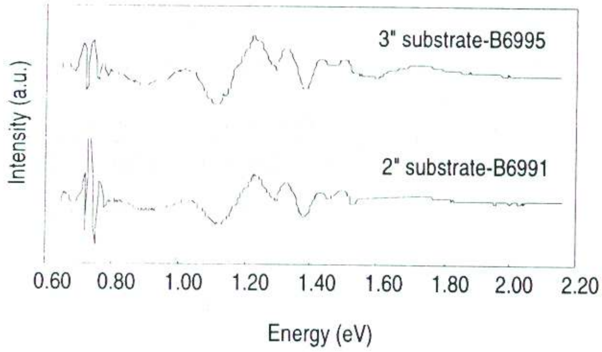

Fig. 2. Photorflectance comparison of two-inch and three-inch InGaAs-InAlAs-InP epitaxial wafers.

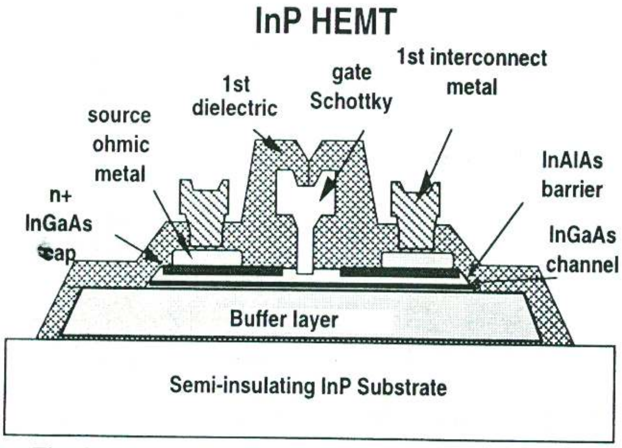

Fig. 3. Baseline InGaAs-InAlAs-InP HEMT profile.

III. InP-Based MMIC Production

The flexible manufacturing InP wafer production flow for both HEMT and HBT MMICs is shown in Fig. 4. About one-half of the steps are shared by both technologies. The manufacturing critical nodes are indicated in bold boxes, and can be divided into two main categories: those that affect transistor performance and those which affect the passive component performance.

The transistor performance critical nodes include epitaxial material growth for both HEMT and HBT, HEMT gate and ohmic contact metal formation, and HBT emitter and base etching. The passive component critical nodes are thin film resistor metalization, MIM capacitor dielectric deposition, and backside wafer thinning. Each of these processes must be well controlled to successfully fabricate high yield InP-based MMICs. Traditional statistical process control methods have been applied to the InP fab line to help monitor process stability, increase process capability, and drive future improvement efforts.

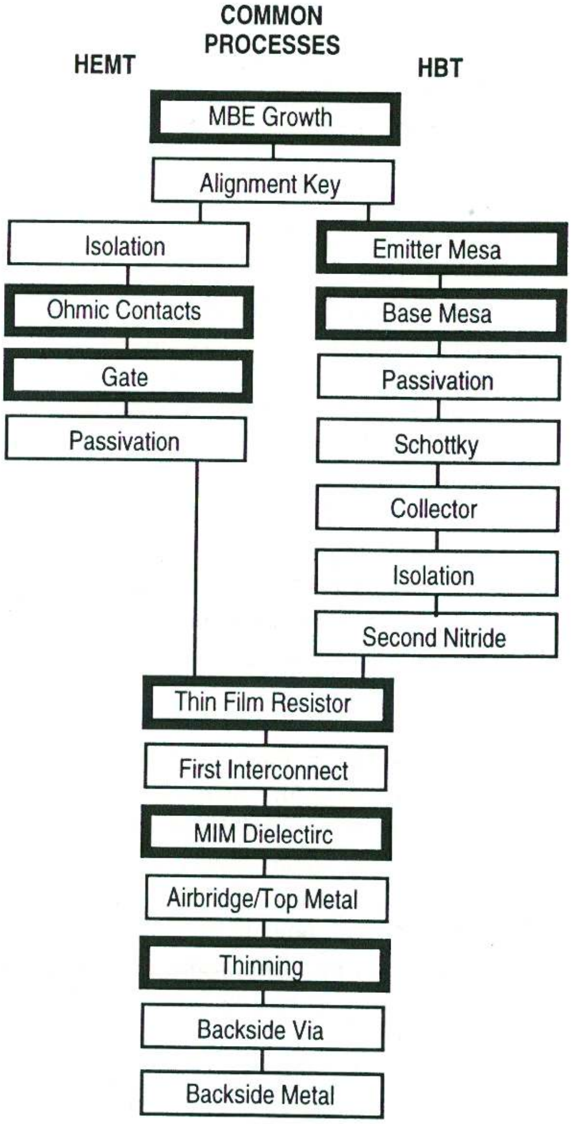

Fig. 4. Flexible InP MMIC manufacturing process flow. Critical nodes are indicated by bold boxes.

IV. Molecular Beam Epitaxy

The most important InP MMIC production critical node is molecular beam epitaxial growth. InP HEMT and HBT device and MMIC performance, reproducibility, and uniformity are ultimately determined by the first and most important step in the process flow, the growth of the device active layers. The MBE profiles for both technologies were transitioned from R&D two-inch substrates to production three-inch substrates. The two goals for this transition were to repeat the profile quality and uniformity on the three-inch wafers, and to obtain a repeatable manufacturing growth process.

Semiinsulating three-inch InP substrates are purchased from several suppliers. Supplier selection is determined from double-crystal X-ray mapping and other material characterization of representative InP substrates.

The quality and reproducibility of the epitaxial layers is trecked in much the same fashion as for our high-volume GaAs processes. Noncontact techniques such as defect mapping, resistivity mapping, X-ray mapping, and photoreflectance are used on device wafers. Special characterization wafers are grown in the same lot with the device wafers, and are cleaved for destrucive analysis such as Hall effect measurements and photoluminescence.

The production repeatibility for three-inch InP HEMT MBE growth is shown in Fig. 5. Electron mobility and sheet density are plotted for monitor wafers that represent over 150 production wafers. The mobility specification is 9000 - 12000 $cm^2/Vsec$. The ±3 sigma process limits are both within the specification limits, demonstrating a process capability Cpk > 1. The InP HEMT and HBT epitaxial growth processes are both well understood and provide the reproducibility required for MMIC production.

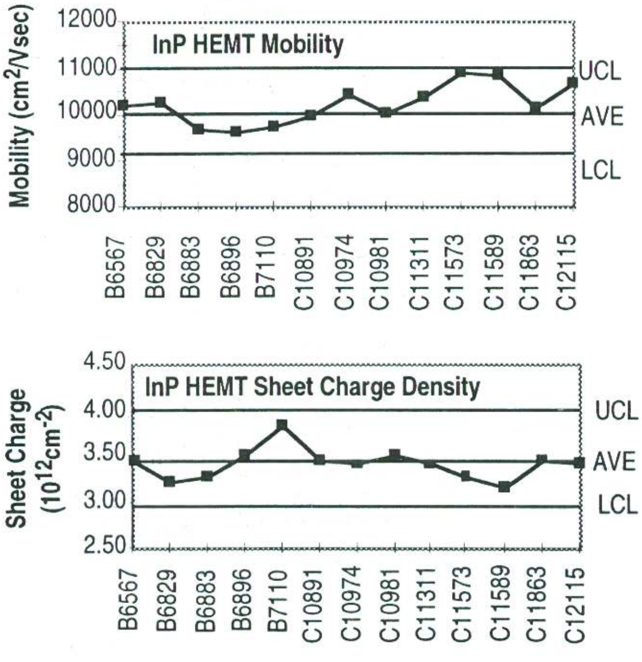

Fig. 5. Post MBE growth mobility and sheet charge density for InP HEMT monitor wafers.

V. InP HEMT Results

The second most important critical node for InP HEMT MMIC production is gate formation. Both physical and electrical parameters are tracked after InP gate formation by electron beam lithography. The key physical parameter is the gate length as measured by scanning electron microscope after gate metal lift-off. The SPC tracking chart for gate length is shown in Fig. 6.

The uniformity of discrete device characteristics across a two-inch wafer is shown in Fig. 7. Electrical parameters were measured for more than 1000 devices on the wafer, and the results are plotted for a drain bias of 0.7V. The average transconductance was 1114 mS/mm with a standard devication of 44 mS/mm (±4%.) The devices were enhancement mode with gm peak occuring at Vg = 0.23 ± 0.04 V.

A family of InP HEMT MMICs has been developed to support low-noise and power applications from 35 GHz to over 200 GHz. An example of the performance capability of these InP HEMT MMICs is demonstrated at 155 GHz using a three-stage low-noise amplifier. Fig. 8 is a photograph of the LNA, Fig. 9 shows gain and input return loss across the 10 GHz band from 148 - 158 GHz. The amplifier achieves 12.5 dB gain from 153 - 155 GHz, with greater than 10 dB gain from 151 - 156 GHz.

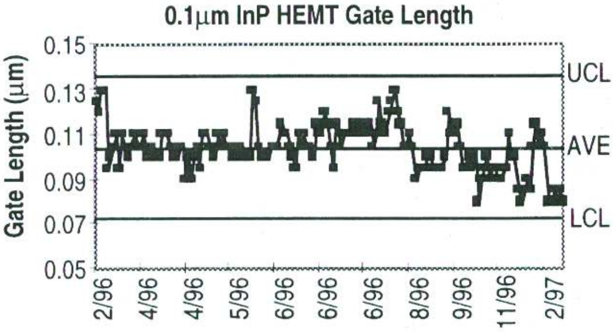

Fig. 6. 0.1µm HEMT Gate Length SPC chart.

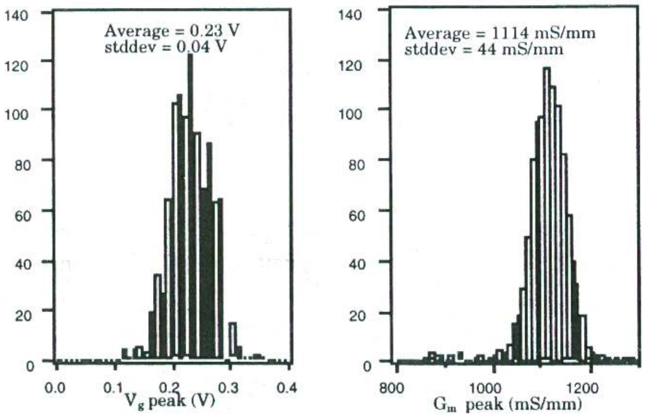

Fig. 7. Histograms of Vgp and Gmp for over 1000 discrete InP HEMT devices on a single two-inch wafer. 0.1 µm x 20 µm device, biased with Vd = 0.7V

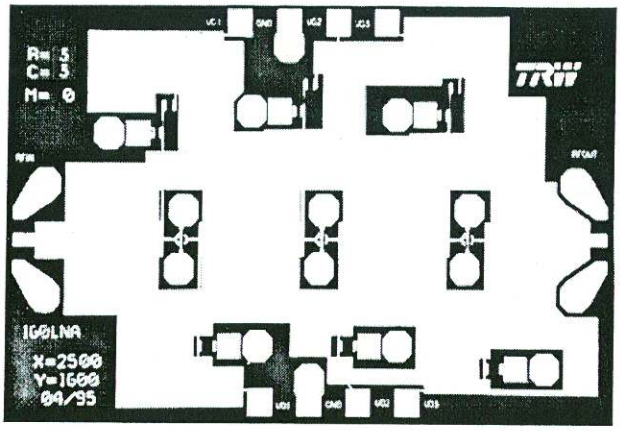

Fig. 8. Photograph of 3-stage InP HEMT MMIC low noise amplifier that achieves 12.5 dB gain at 155 GHz.

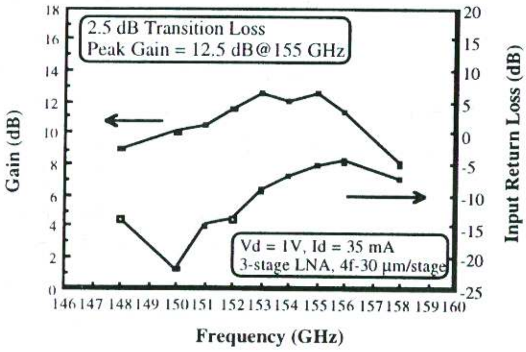

Fig. 9. Gain and input return loss for the 155 Ghz HEMT amplifier shown in Fig. 8. Vd = 1.4V, Id = 25 mA.

An example of 0.1 μm gate-width InP HEMT uniformity across a three-inch InP substrate is shown below in Fig. 10 for a W-band low noise amplifier with ~18 dB gain at 94 GHz. This is a production 0.1 μm process with reproducible and uniform HEMT MMIC performance, typical fT = 200 GHz, fmax = 350 GHz.

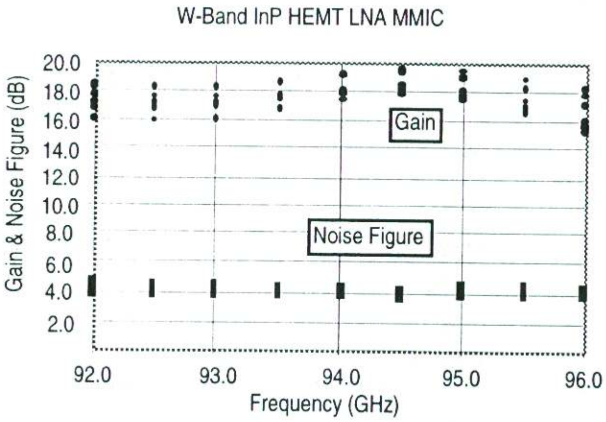

Fig. 10. Gain and noise figure for InP HEMT MMIC low-noise amplifier across a three-inch wafer.

VI. InP HBT Results

The InP HBT emitter and base mesa critical nodes are parameters associated with transistor performance. These transistor parameters are key measures of the process stability for the HBT technology.

Fig. 11 shows the distribution of base-emitter voltage V_{be} and current gain ß for an InP HBT production run of 96 three-inch wafers. The values are wafer averages. The V_{be} is measured at 10 μA to minimize series resistance effects, while the current gain is measured at 4 mA on a $1x10\mu m^2$ emitter device. Average Vbe is 0.575 V. The compositionally-graded InGaAlAs base-emitter junction functions to minimize both absolute Vbe and variation across the wafer. There values are also governed by the coincidence of the base-emitter p-n junction and the InGaAs-InAlAs graded heterojunction. Excellent p-type doping control results in minimumVbe and excellent Vbe matching on the order of a few mV.

In addition to DC parameters, RF parameters are also tracked as critical parameters. The cutoff frequency f_t is plotted in Fig. 12 for a $1X10\mu m^2$ quad emitter HBT as a function of lots processed, each lot representing six three-inch wafers. The data exhibits lot to lot repeatability of ±6% and an The average cutoff frequency is 65 Ghz at 80 kA cm^{-2}, biased at Vce = 2V, with a standard deviation of ±6% over the 16 lots.

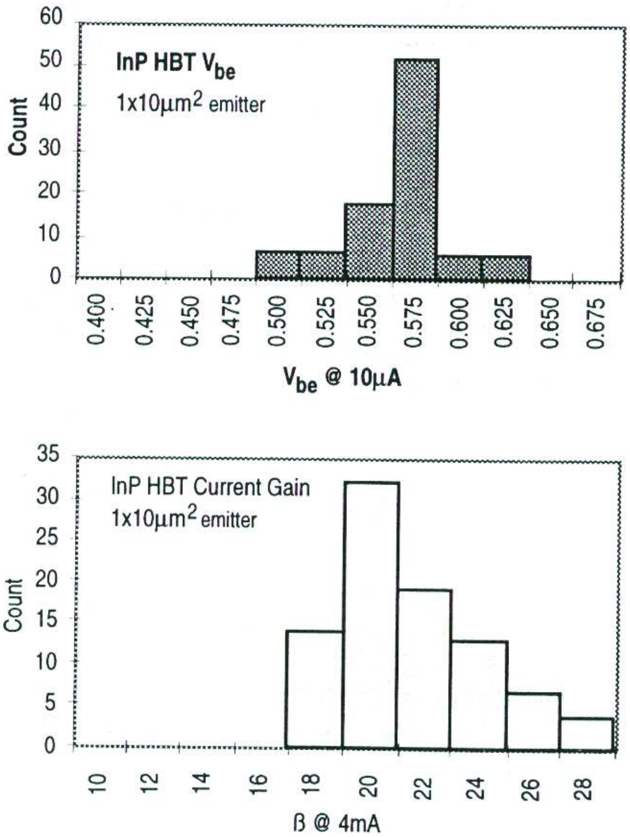

Fig. 11. Base-emitter voltage and current gain distribution for an InP HBT production run of 96 three-inch wafers.

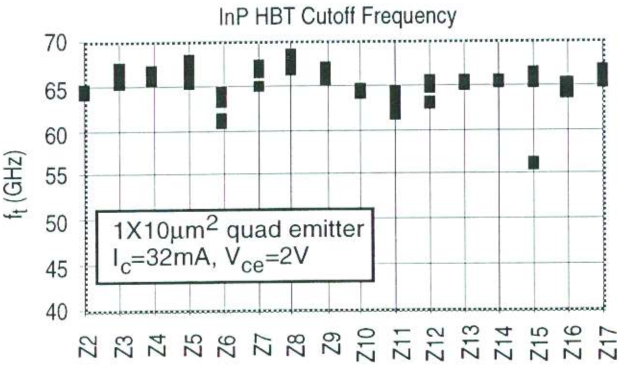

Fig. 12. Cutoff frequency fT for a 16-lot three-inch InP HBT production run, six wafers per lot.

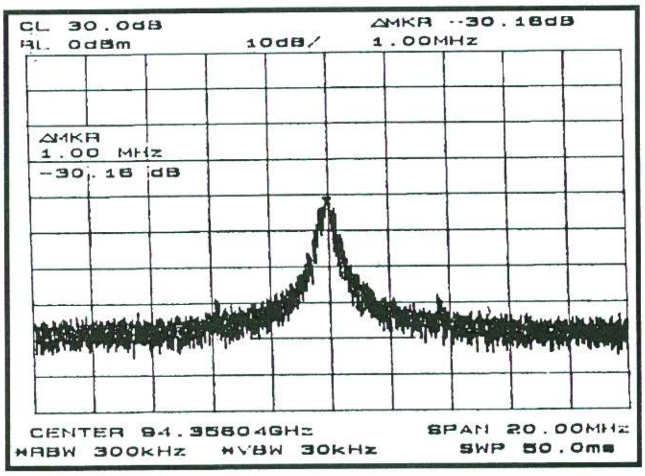

Fig. 13. Output power spectrum of fundamental mode W-Band InP HBT VCO.

Fig. 13 shows the output power spectrum of a monolithic fundamental mode W-Band VCO in the 1 μm InP HBT process. The measured oscillation frequency is 94.7 Ghz and the peak output power is -3.5 dBm. This is the highest frequency fundamental mode oscillator ever reported using bipolar device technology.

Over 50 different MMIC designss including LNAs, mixers, frequency converters, VCOs, and high linearity amplifiers from X-Band through W-Band have been manufactured using the InP based MMIC processes.

VII. Passive Components

Several critical nodes and parameters have also been defined for InP MMIC production for the passive components. The critical parameters are thin film resistor sheet resistance, capacitor dielectric thickness and final substrate thickness after thinning. These parameters, as well as the transistor critical parameters, can also critically impact MMIC performance and yield. An example of one of these is shown in Fig. 14 where the sheet resistance of the TFR film is plotted for runs over the last year. The process capability Cpk is 0.96.

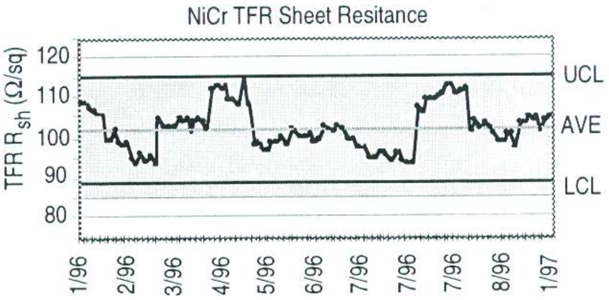

Fig. 14. SPC chart for TFR sheet resistance.

VIII. Conclusion

InP based MMICs provide key performance advantages compared to GaAs in terms of noise figure, frequency performance, power consumption, and linearity for government and commercial production applications. TRW has transitioned InP MMIC fabrication from R&D to production. Key elements of this transition were the use of statistical process control techniques and a drive toward process commonality between the InP HEMT and HBT technologies. We have demonstrated reproducible HEMT and HBT processes using three-inch InP substrates, and hev developed process capability necessary for high-volume InP HEMT and HBT MMIC production. MMIC performance for the production process compares well with the R&D performance, which has resulted in record InP HEMT and InP HBT performance.

Acknowledgments

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