drain-source breakdown voltage of approximately 7 V. When measured with the connection shown in Fig. 15, the gate current increased rapidly as V_{dg} approached 9 V because of the drain-source breakdown. As a result, the gate current versus V_{dg} became similar to the one obtained with Fig. 14. Thus there was no need to distinguish V_{SB} obtained by the two methods with conventional FET's.

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Some Aspects of GaAs MESFET Reliability

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Abstract—**The results of a short study into the reliability and failure modes of GaAs MESFET's are presented. Two failure modes have been observed during this study and improved fabrication techniques that reduce their occurrence have been examined. The results obtained indicate that extremely reliable devices can be manufactured with a predicted mean time to failure in excess of 10^7 h at junction temperatures of 70°C. Room-temperature life tests in excess of $\frac{1}{2}$ million device hours lend support to these predictions.**

I. INTRODUCTION

THE past few years have seen the emergence of the GaAs MESFET as a microwave transistor of tremendous potential. It combines low noise, high gain, and large dynamic range at frequencies unlikely to be reached by bipolar devices. There have been many papers published on its applications [1]–[3] and its variants [4]–[8], but little has been reported on the long-term reliability of the device. With the imminent prospect of MESFET amplifiers being used in space applications [9], device reliability is of prime importance.

This paper presents the results of stress testing on a number of *X*-band devices with different metallization systems. Four different ohmic contact systems were tested:

1) gold/germanium (Au/Ge);
2) indium/gold/germanium (In/Au/Ge);
3) nickel/gold/germanium (Ni/Au/Ge);
4) platinum/gold/germanium (Pt/Au/Ge).

The devices with Au/Ge metallization had a passivation layer of silicon monoxide covering the channel area and parts of the drain and source contact, and the Pt/Au/Ge devices had an overplate of a thin chromium (Cr) layer and a thicker Au layer.

The tests performed included reverse biasing of the gate diode at an elevated ambient temperature, thermal cycling from −65 to +150°C, ac modulation of the drain current by application of gate volts to turn the device on and off,

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and high-temperature dc and RF tests. From these tests two failure modes emerged; the susceptibility of the gate diode to spike burn-out, and migration of the ohmic contact metallization at high junction temperatures. These two failure modes are treated in more detail in the Sections II and III.

Following the identification of these two failure modes, further experiments were conducted to isolate the factors involved. Variations in processing and device design were investigated, yielding improvement in both areas.

The work performed was mainly concerned with identifying the problem areas and evaluating possible solutions. One valuable aid was the use of nematic liquid crystals to identify hot spots on devices and to obtain thermal profiles for the different contact configurations encountered. Some work was done on extrapolating accelerated test data to give a room-temperature failure rate. This is reviewed in the final section of this paper.

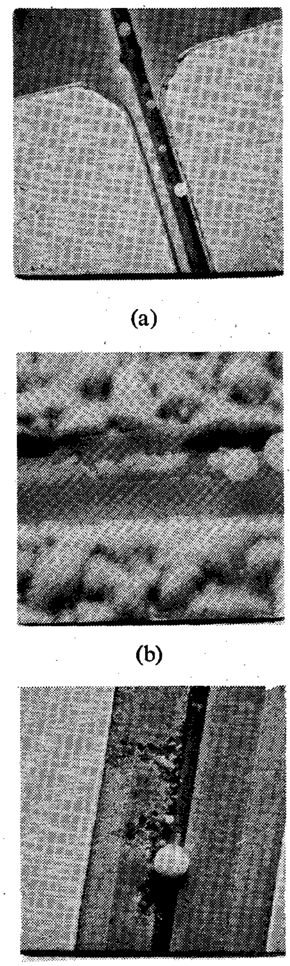
II. Gate Diode Burn-Out

Testing of the gate diode was performed in two parts. Firstly, the devices had their gates reverse biased, with respect to the source and drain, to two-thirds of the room-temperature breakdown voltage. They were run under this bias condition in an ambient temperature of 150°C and the gate leakage current was monitored. Secondly, the devices, with zero gate bias, were exposed to large spikes from the output of a T-R cell. The spike amplitude was increased gradually and the device noise figure monitored until the devices failed.

Throughout the duration of testing at 150°C the gate leakage currents did not change in any regular fashion. Some increased and some decreased. When biased close to breakdown, though, the devices are more susceptible to transient spikes which can cause punch through of the channel or bias the gate to breakdown, giving a large current flow in the gate. While on a reverse-bias test, the devices were subjected to spikes on the gate, source, and drain. This resulted in the failure of several devices. The most tolerant devices were those with the In/Au/Ge ohmic contacts. As all the devices tested had Al gate metallization, the variations in resistance to spike inputs were due to differences in the manufacturing technology of the devices.

As this was only a qualitative test, the best devices were subjected to spikes from a calibrated T-R cell. The device noise figure was monitored but was found not to change with spike input until the device catastrophically failed. This is in contrast with mixer diode results where noise figure degradation is normally experienced and used as a failure criterion [10], [11]. The aluminum gate devices had a mean energy for device failure of 0.3 erg/spike, each spike being about 1.5 ns in duration.

Several papers have been published on improving the burn-out performance of mixer diodes [10], [11]. The general conclusion is that improved burn-out performance is obtained by using a high melting point refractory metal for the Schottky barrier. Accordingly, devices with Ni gates and In/Au/Ge ohmic contacts were tested. These devices, having similar gain and noise figure to those with



(a) (b) (c)

Fig. 1. The formation of spheres of metal due to spike breakdown of the gate; devices had source and drain contacts of (a) In/Au/Ge, (b) Au/Ge, and (c) Pt/Au/Ge with overlay of Cr and Au.

Al gates, gave a mean energy at failure of 2.3 erg/spike, a significant improvement.

Haythornthwaite *et al.* have also reported on spike breakdown of the Schottky barrier gate in GaAs MESFET's [12]. The failure modes they observed were the same as those seen in the present work. Spike breakdown causes localized heating, sometimes resulting in the formation of spheres of material and holes in the channel region. This can cause the gate to open circuit or to short circuit, giving a catastrophic failure. Typical failures are shown in Fig. 1(a)–(c). Fig. 1(a) shows In/Au/Ge ohmic contacts, the drain on the left, source on the right with the gate between. Fig. 1(b) shows Au/Ge contacts overlayed with silicon monoxide. The drain is at the top, source at the bottom, and the gate between them. Fig. 1(c) is of the Pt/Au/Ge system with the drain on the left and source on the right. The layer adjacent to the gate is the Pt/Au/Ge ohmic contact. Moving outwards on both sides there is the Cr then the Au overplate. There is also a correlation between failure sites and manufacturing defects. Irregularities in the gate metallization and channel region can provide weak points where failure occurs.

It is possible to take precautions to minimize the chance of damage from accidental spike breakdown.

1) During all handling stages the operator should wear a grounding strap to reduce static potentials.

2) When the device is connected into a circuit there should be a dc path to ground for the gate.

3) Avoid switching the supply voltage to any equipment directly connected to the device.

4) Minimize the length of bias leads, and avoid the switching of highly inductive loads in the vicinity of the device. This reduces the pickup of airborne interference.

III. Metal Migration

Metal migration, the current induced transport of material, appears to have been first correctly identified as a potential cause of failures in microcircuit interconnection around 1965 [13]. Since then there has been a lot of work done on identifying the causes of migration and evaluating preventive measures. Without question, at some elevated temperature metal migration effects can be observed in all semiconductor devices—what is important is to determine the conditions under which this occurs in the GaAs MESFET. The results in this section show that metal migration does indeed occur but only noticeably at junction temperatures around 250°C, and so does not represent a serious hazard to high reliability usage.

In order to accelerate the migration and shorten the time to failure, the GaAs MESFET's were subjected to dc biasing at an ambient temperature of 200°C (i.e., 250°C junction temperature). The devices were run at +5-V drain bias with the gate grounded, giving a current density of about 10^5 A/cm^2. Under these conditions migration effects were observed on all devices tested within 1000 h. Following the initial observation of metal migration, further experiments were carried out to assess the effect of contact shape on the time to failure. Finally, some amplifiers operating at 11 GHz were tested to determine the effect of elevated temperatures on their microwave performance.

With Au/Ge and In/Au/Ge ohmic contacts the combination of time, temperature, and current caused material to accumulate at the edge of the source contact adjacent to the etched channel, and to deplete the drain contact at a similar place. Fig. 2, with the source on the right and drain on the left, illustrates this effect. Microprobe analysis confirmed that the accumulated material was that of the ohmic contact. It is not believed, though, that the material crosses the gate region, but that it moves across the contact from the source bond area towards the edge of the source contact, and from the edge of the drain contact to the drain bond area. This direction of material transport is the same as that of electron flow, and thus agrees with present explanations of migration [16]. Nodules of material have been seen on the drain bond wire which were not present when the devices were put on test (Fig. 3).

For the Ni/Au/Ge system the primary effect under high-temperature stress was the "balling" of the metallization causing increased contact resistance. Heime *et al.* [15] observed a similar effect when alloying the contact, but found that evaporation of a thin nickel layer on top of the Au/Ge before alloying could reduce the balling. In the devices tested there was no evidence of balling after alloying; this only appeared after high-temperature testing. The increased contact resistance reduces the drain current and transconductance and leads to a general deterioration in microwave performance.

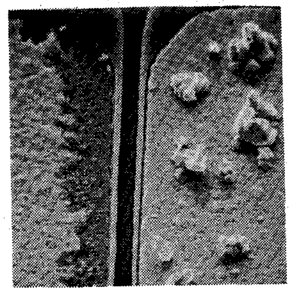
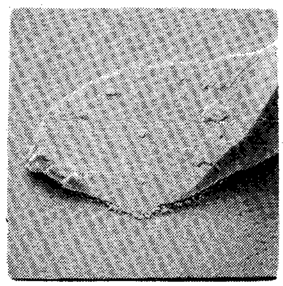


Fig. 2. Depletion and accumulation of In/Au/Ge contact after temperature stress testing.



(a)

(b)

Fig. 3. Accumulation of ohmic contact alloy on the bond wire to GaAs MESFET. (a) Initial state of bond wire. (b) Nodule formation on bond wire.

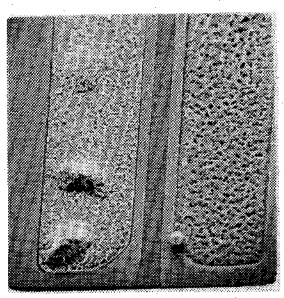


Fig. 4. Swellings under source contact of a Ni/Au/Ge contact after stress testing.

Where material accumulation was expected on the source contact there were several noticeable swellings. Fig. 4 shows the source on the left and the drain on the right. This seems due to the migration of a metallized layer under the more resistive balled layer. The composition of

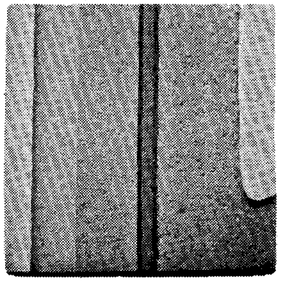


Fig. 5. Depletion of chromium layer on drain contact of device with chromium overlay metallization.

the migrating material has not been determined as it is covered by the surface layer of the ohmic contact. Depletion of the drain contact also took place in a modified form due to the balling. There was significantly less material in the areas where depletion was expected, and nodules of material once again appeared on the drain bond wire.

With the Pt/Au/Ge metallization system the ohmic contacts had an overplate of chromium followed by a thicker gold layer. During temperature stressing, the chromium layer on the drain contact showed marked signs of migration and the edge of ohmic contact was noticeably depleted. Material also began to build up on the source contact. Fig. 5 has the source on the left and the drain on the right.

Three ohmic contact shapes were examined—T-shaped triangular, and rectangular—to evaluate their effect on the time to failure. It was found that the accumulation rate, depletion rate, and the positions of accumulation and depletion were all affected by contact shape. Thermal profiling with a nematic liquid crystal [14] showed that these differences were caused by localized hot spots due to current crowding in the contact. The positions of these hot spots were also affected by the "heat-sinking" effect of the bonds. The migration rate was slowest for the rectangular and fastest for the T-shaped contact. Migration occurred mainly at the ends of the T-shaped contacts, at the apex of the triangular contacts, and was distributed evenly along the edge of the rectangular contacts.

In order to assess the effect of temperature stressing on microwave performance, some X-band amplifiers, with In/Au/Ge ohmic contact and aluminum gate devices, were operated in a 100°C ambient. RF input power was about 2 mW CW at 11 GHz, and typical dc input was 150 mW. After 2000 h of testing under these conditions there were negligible changes in the amplifier gain and noise characteristics. None of the devices showed signs of metal migration or any other physical deterioration.

IV. Reliability Modeling

To properly assess the device lifetime, the functional relationship between the time to failure and the applied stresses must be known. Extrapolation from accelerated to normal conditions is then possible. Although the data obtained in this study are not sufficient for this to be done, this exercise has been performed for metal migration failures by other workers [16] and found to have the Arrhenius form

$$\mathrm{MTF} = AJ^{-n} \exp\left(\frac{E_A}{kT}\right) \tag{1}$$

where A is a constant of proportionality, J is the current density, n is a constant, E_A is an activation energy, k is Boltzmann's constant, and T is the absolute temperature. If it is assumed that A, J, and n remain constant with time and temperature, then

$$\frac{\mathrm{MTF}\ (\text{at } T = T_1)}{\mathrm{MTF}\ (\text{at } T = T_2)} = \frac{\exp\left(\frac{E_A}{kT_1}\right)}{\exp\left(\frac{E_A}{kT_2}\right)}.$$

If T_1 and T_2 represent room and test temperatures, respectively, then an estimate of mean time to failure can be made if a value for E_A is assumed. There are no published data for Au/Ge based metallization systems, but Oliver and Bower [17] obtained a value of 1.0 eV for Au. This activation energy gives an extrapolated mean time to failure for room-temperature operation of devices with Au/Ge based ohmic contacts in excess of 10^7 h.

V. Conclusions

In currently produced small-signal GaAs MESFET's two failure modes are dominant: spike burn-out of the gate diode and, at high ambient temperatures, metal migration of the ohmic contact. A qualitative assessment has been made of different device structures and metallization systems which has shown the way to improving device reliability.

The occurrence of spike burn-out of the gate can be reduced in two ways; careful handling can increase reliability on present devices, while the intrinsic burn-out resistance can be increased by use of a high-melting-point refractory metal for the Schottky barrier. Nickel is nearly an order of magnitude better than aluminum in this respect.

Reduction of the high temperature metal migration can also be accomplished in several ways. The current density can be reduced by making the metallization thicker, but due to limits exposed by the float-off process used to define contact area, plating up of the contacts is necessary to achieve maximum effect. The contact shape, by influencing the current distribution in the contact, also influences the migration. Rectangular contacts give the most uniform distribution of current and therefore are the most promising. As the migration is dependent on junction temperature, improvements in mounting techniques to reduce the thermal impedance could also give improvements in reliability.

To obtain the optimum noise performance from the GaAs MESFET, it is necessary to bias them to low drain currents. This is beneficial to the device lifetime as it reduces both the current density and junction temperature.

Preliminary results on small-signal MESFET's with In/Au/Ge ohmic contacts have given a mean time to failure in excess of 10^7 h. This compares with the only other published data for GaAs MESFET's of 10^6 h [18]. This MTTF is in excess of that required for most high reliability applications and the devices have already undergone successful qualification for space flight use [9]. These predictions of excellent reliability of the GaAs MESFET are reinforced by long-running device life tests at room temperature where 11 devices have so far accumulated $\frac{1}{2}$ million device hours with no device failures, a failure being defined as a parameter change greater than 10 percent.

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Reliability Study of GaAs MESFET's

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***Abstract*—Failure modes have been studied phenomenologically on a small-signal GaAs MESFET with a 1-μm aluminum gate. Three major failure modes have been revealed, i.e., gradual degradation due to source and drain contact degradation, catastrophic damage due to surge pulse, and instability or reversible drift of electrical characteristics during operation. To confirm the product quality and to assure the device reliability, a quality assurance program has been designed and incorporated in a production line. A cost-effective lifetime prediction method is presented that utilizes correlations between RF parameters and dc parameters calculated using an equivalent circuit model. Mean time to failure (MTTF) value of over 10^8 h has been obtained for the GaAs MESFET for an operating channel temperature of 100°C.**

I. INTRODUCTION

BECAUSE of its inherent superiority in high-frequency and low-noise capabilities, the GaAs MESFET is now establishing a firm position in the family of microwave semiconductor devices. Recent progress in device design and in manufacturing technology has demonstrated that commercial production of small-signal GaAs MESFET's is feasible, and the device is now being used in practical low-noise amplifiers for C- to X-band frequencies.

In order for the GaAs FET's to be used extensively and reliably in many applications, it is necessary to establish a reliability assurance system, which should be based on a cost-effective means of life prediction. Such a reliability assurance system is particularly important in space applications and in some sort of communication systems, where an extremely high degree of reliability is required.

The purpose of this paper is to present the results of our investigations of the following three problems: 1) What kinds of failure modes exist that govern the reliability of the GaAs MESFET? 2) How and what quality assurance program is to be designed to manufacture high reliability GaAs MESFET's? 3) How can the operational lifetime or reliability be evaluated or predicted with cost-effective techniques?

The investigations have been made on a GaAs MESFET with

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