A Monolithic Single-Crystal Yttrium Iron Garnet/Silicon X-Band Circulator

S. A. Oliver, P. M. Zavracky, N. E. McGruer, and R. Schmidt

***Abstract*—Production of truly monolithic microwave integrated circuits that incorporate ferrite passive control elements has been hindered by the material property mismatches between ferrites and semiconductors. In this work, monolithic Y-junction circulators were fabricated by bonding 100-μm-thick single-crystal yttrium iron garnet films to silicon at 195 °C, and then removing the gadolinium gallium garnet substrate. S-parameter measurements on the circulator and matching microstrip circuit yield an isolation of 20 dB over a 1-GHz bandwidth at 9 GHz, with a minimum insertion loss near 1 dB. Improvements in circuit design and fabrication techniques may yield monolithic circulators that are fully compatible with large-scale semiconductor manufacturing methods.**

***Index Terms*—Bonding, ferrimatnetic films/devices, ferrite circulators, microwave circulators, MMIC's, scattering parameters measurement.**

I. Introduction

THE RAPID growth in telecommunications has quickened development of monolithic microwave integrated circuit (MMIC) systems and related technologies. The promise of large production runs to meet this burgeoning commercial market is overcoming the substantial start-up costs of MMIC-based systems, making them competitive with hybrid microwave integrated circuits. Despite steady advances in semiconductor MMIC components, however, the pursuit of fully monolithic systems to replace current hybrid systems is being hindered by the necessity of connecting off-chip to passive control elements. In particular, ferrite-based control elements, such as circulators or isolators, have proven difficult to fabricate monolithically on semiconductor substrates using standard processing methods.

The difficulties involved in integrating ferrite films with semiconductor materials arise from several sources. First, the electromagnetic coupling in gyromagnetic materials is weak, which leads to device designs that require the ferrite film to be tens to hundreds of times thicker than other metallization or dielectric films in the circuit. Second, the process conditions required to obtain high-quality ferrites include both temperatures over 700 °C and oxidizing atmospheres [1]. It is difficult to reconcile either of these growth conditions with standard wafer-processing techniques if one attempts to directly deposit ferrites onto previously metallized semiconductor wafers. Third, a substantial difference in the coefficient of thermal expansion exists between most ferrites and semiconductors, leading to large stress at the ferrite/semiconductor interface as the wafer is cooled to ambient temperature from the high growth and processing temperatures. Combined, these three sources yield a difficult materials problem, especially for the direct ferrite deposition method. Although researchers have previously demonstrated circulators on alumina substrates [2], [3], only recently have monolithic circulators been successfully produced on silicon or gallium arsenide by direct ferrite film growth [4].

In this letter, we present test results on a monolithic X-band Y-junction circulator that has been fabricated on silicon at temperatures under 200 °C. In contrast to most previous procedures for fabricating monolithic circulators, our method involves bonding a thick ferrite film onto the semiconductor substrate. Since the ferrite film is grown on a native substrate separate from the integration process, in principal it can possess optimal parameters for the device application. After bonding, the native substrate is removed using planarization techniques, leaving the ferrite top-surface accessible for device fabrication. This method appears to have great flexibility with respect to the ferrite and semiconductor materials used.

II. Circulator Fabrication and Testing

The ferrite used to fabricate the monolithic circulators was a 100-μm-thick (111)-oriented single-crystal film of yttrium iron garnet (YIG), purchased as a 3-in wafer from the Airtron Co. This film was grown by liquid phase epitaxy onto a lattice matched gadolinium gallium garnet (GGG) substrate. The ferromagnetic resonance linewidth of the YIG film was under 0.5 Oe. This wafer was diced into 0.50 $\times$ 0.40-in die for bonding, as was the semiconductor wafer. Here, the semiconductor was a highly doped 3-in silicon wafer with a 2-μm top layer of silver providing part of the circulator ground plane.

The conductivity of the circulator ground plane was further improved by depositing a 2.5-μm-thick copper film and a 100-nm-thick TiW passivation layer onto the exposed YIG film face before depositing the bonding alloy films. A solid-liquid interdiffusion bonding process was used [5], with the precursor material consisting of elemental films of gold and indium having a total gold weight fraction near 12 wt.%Au. Elemental films of first gold, and then indium, were deposited onto the mating faces of both die before bonding. The mated

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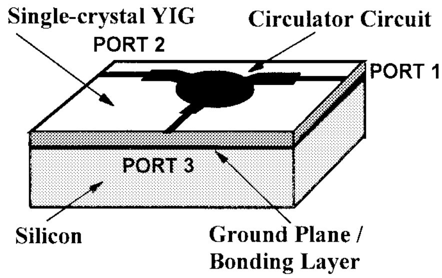

Fig. 1. A schematic showing the components of a monolithic integrated YIG/Si Y-junction circulator. The biasing magnet is not shown.

die were then bonded under vacuum in a graphite strip heater at a temperature of 195 °C. The structure of the bonding layer resulting from this process shows islands of precipitated AuIn intermetallic alloys in an indium matrix. The AuIn intermetallic alloys have greater mechanical strength than either elemental film, and melting temperatures over 450 °C. Thus, this bonding layer has good mechanical strength while retaining some compliancy to stress.

A Buehler MiniMet polishing unit was used to grind the native GGG substrate from the bonded die. After exposing the ferrimagnetic YIG film, the top surface underwent chemical-mechanical polishing to reduce surface roughness. In general, the tolerance of the grinding unit limited the surface planarity of the dice to about 10 μm, while profilometer measurements showed a mean surface roughness of 12 nm. After the top surface was metallized with 2.5 μm of copper, the circulator junction and matching microstrip circuit were patterned photolithographically and then etched using standard semiconductor techniques. A schematic of the resulting monolithic circulator is shown in Fig. 1.

The Y-junction circulator and matching network were modified from standard designs used for thick ceramic ferrite pucks to meet the new requirements of 100-μm-thick ferrite devices. Most circulator models do not incorporate the ferrite thickness as an initial design parameter. In addition, it was suspected that conduction loss in the microstrip impedance-matching circuit may be the largest loss contribution for ferrite film circulators. Thus, this design, which will be discussed at length elsewhere, compromises between the requirements of standard circulator models and the need to minimize conductivity losses. This was obtained by reducing the circulator coupling angle to allow direct connection between the low-impedance circulator port output and the 50-Ω connectors by a quarter-wave transformer. In practice, this design appears to improve the device insertion loss compared to devices having multiple transformer stages, but at a cost of bandwidth. The designed center frequency of the microstrip impedance-matching circuit was 9.5 GHz.

A Hewlett-Packard 8510B vector network analyzer was used in taking S-parameter measurements over the frequency range from 6 to 18 GHz. The magnetic bias field was provided by a samarium cobalt permanent magnet having a diameter roughly equal to the junction. This magnet was offset from the junction by alumina spacers in order to obtain an internal magnetic field of approximately 300 Oe. Miniature (SMA) tab-launchers were used to connect from the microstrip to external coaxial cables. Ground plane connections were made through

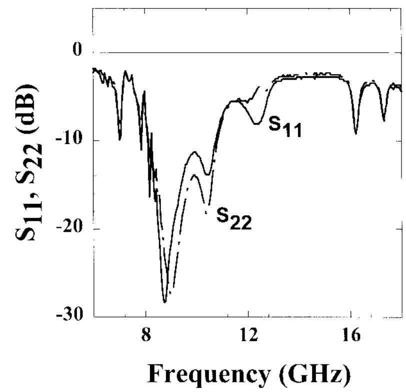

Fig. 2. Reflection measurement results for a monolithic YIG/Si Y-junction circulator.

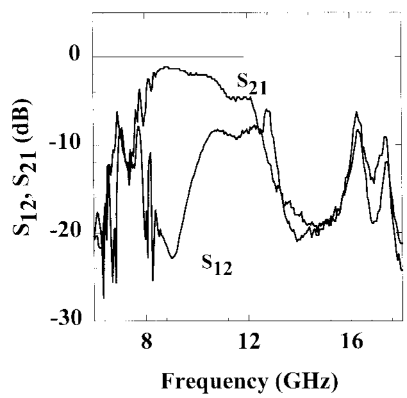

Fig. 3. Transmission measurement results for a monolithic YIG/Si Y-junction circulator.

silver print painted on the dice sides, due to the inaccessibility of the ground plane to direct electrical connections. Test results were taken between ports 1 and 2, as shown in Fig. 1, while port 3 was terminated in a 50-Ω load.

Fig. 2 shows the reflection measurements S_{11} and S_{22} for a circulator circuit. The reflections from both ports are similar, although the center frequencies for the two ports differ slightly from each other and from the designed value. Transmission through the circulator is shown by the S_{12} and S_{21} measurements of Fig. 3. These results show isolation over a 4-GHz band, with over 20 dB of isolation shown over a 1-GHz band centered at 9 GHz. The lowest measured insertion loss in this frequency band was 1.2 dB, also near 9 GHz. Since these measurements include losses in the SMA launchers, which contribute an estimated 0.2 dB to the measured loss, the lowest insertion loss for the monolithic circulator circuit lies near 1 dB. Strong peaks are seen in all S-parameter measurements at frequencies below 8.5 GHz, effectively reducing the circulator bandwidth. The source of this frequency dependence is unclear, but may be caused by nonuniform magnetic fields in the single-crystal ferrite film.

Several improvements should be made in the Y-junction circulator design, fabrication, and testing, based on an assessment of these results. Circulator designs need to be developed for single-crystal ferrites and must account for intrinsic properties such as magnetocrystalline anisotropy. An improvement in insertion loss of 0.2 dB for the present circuit could be expected through improved ground plane connections and better YIG planarization, where the latter improvement will reduce impedance mismatches in the microstrip circuit. In addition, the circulator bandwidth can be broadened by using a magnetic circuit that provides a homogeneous magnetic field in the junction.

III. Conclusion

Monolithic single-crystal YIG/Si X-band circulators have been fabricated using a solid-liquid interdiffusion bonding method. Test results on these circulators show insertion loss near 1 dB and 20-dB isolation over a 1-GHz bandwidth. Further improvements in the design of appropriate Y-junction circulators, and in the fabrication process, may make large scale manufacturing of high-performance circulators for truly monolithic MMIC systems possible.

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