A Survey to
Monolithic Microwave Integrated Circuit Design Technology

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ABSTRACT
The design of MMICs is essentially the same as that for most microwave components: one or more signals must be coupled onto the chip efficiently, then functions are performed on the signals, after which they are then coupled out of the chip and back into the system. the efficient coupling of signal power requires that the impedance of the signal source match that of the chip. In fact, to pass the signal efficiently through the whole chip, the impedances of the transmission lines, the active devices, and the system it sits in must all be matched. MMIC design is founded on impedance matching and control across the frequency range of interest. *Gain* and *Noise Figure* of a typical transistor is decreased and increased in terms of frequency increase, respectively.

1. INTRODUCTION
The acronym MMIC stands for monolithic microwave integrated circuit. The word monolithic means "as a single stone" and describes the fundamental characteristic of MMICs (i.e., that they are fabricated from a single piece of semiconductor material). The word *microwave* refers to the ac signal frequency range within which they are used, which covers free-space wavelengths from 1 mm to 1m and corresponds to frequencies from 300 MHz to 300 GHz. The term *integrated circuit* (IC) indicates that the semiconductor material does not contain a single diode or transistor but consists of an electronic circuit of active devices, like transistors, and passive devices, such as capacitors and resistors, together with all their interconnections, to make up a whole system.

MMICs are utilized in most applications that involve transmitting and receiving microwave signals, ranging from cellular phones, wireless local-area networks (WLANs) and Global Positioning System (GPS) receivers at the low gigahertz end up to Earth-observation radiometers and security scanners up in the hundreds of gigahertz end. They have applications in the communications industry within optical-fiber, satellite communications, and point-to-point links; in the automotive industry within vehicle identification, road-traffic information, and cruise-control systems;

and in the military industry within electronic warfare, missile seeker heads, and phased-array radar systems.

1.1 The History of MMICs
One of the first silicon ICs operating at microwave frequencies (silicon MMIC) was an X-band transmit/receive switch developed in 1966. In 1967, GaAs field effect transistors (FETs) showed the capability to operate at microwave frequencies, and Plessey produced GaAs metal semiconductor field effect transistor (MESFET). in 1970, GaAs FETs were reported, for the first time, to outperform silicon transistors at microwave frequencies.

2. ACTIVE COMPONENTS
The active components on an MMIC are those that provide voltage or current gain to the signals on the chip-in other words, the transistors. These are known as active devices because they can use DC bias power to increase the RF signal power actively within the circuit and even to generate the signals in the first place.

2.1 Substrate Material
The most commonly used substrate materials are silicon (Si) and gallium arsenide (GaAs), where Si is traditionally used for RF and lower frequencies and GaAs is used for microwave and millimeter-wave frequencies. However, with the advancement of silicon

germanium (SiGe) transistors, the frequency response of circuits on Si substrates is pushing firmly into the microwave-frequency region. More exotic substrate materials, such as indium phosphide (InP), are tending to take over from GaAs as frequencies extend beyond 100 GHz [1]. Other substrate materials that are increasingly being used include silicon carbide (SiC) [2] and gallium nitride (GaN) [3]. The characteristics of these commonly used semiconductor materials are shown in Table 1

Table 1: Characteristics of the Most Commonly Used Semiconductor Materials

Material	Electron Mobility (cm2/Vs)	Peak Velocity (*10^7 cm/s)	Frequency Range (GHz)	Noise Figure	Gain	Comments
Si	900–1,100	0.3–0.7	< 20	Moderate	Moderate	Mature process; 12-in. wafers
SiGe	2,000–300,000	0.1–1.0	10–40	Lower	Better	Benefits from Si; 6-in. wafers
SiC	500–1,000	0.15–0.2	15–20	Poor	Lower	4-in.wafers
GaAs	5,500–7,000	1.6–2.3	>75	Lower (Fmin at 26 GHz =1.1 dB)	Higher(Gass at26 GHz =9.0)	Less mature than Si;3-, 4- and 6-in.Wafers
GaN	400–1,600	1.2–2.0	20–30	Poor	Lower	Less mature than GaAs; Vbr >100V; 2-in.Wafers
InP	10,000–12,000	2.5–3.5	>115	Lower (Fmin at 26 GHz =0.9 dB)	Higher(Gass at26 GHz=11.1)	Less mature than GaAs; 2-in.wafers

A graph showing the typical output power from various transistor technologies as a function of frequency is shown in Figure 1.
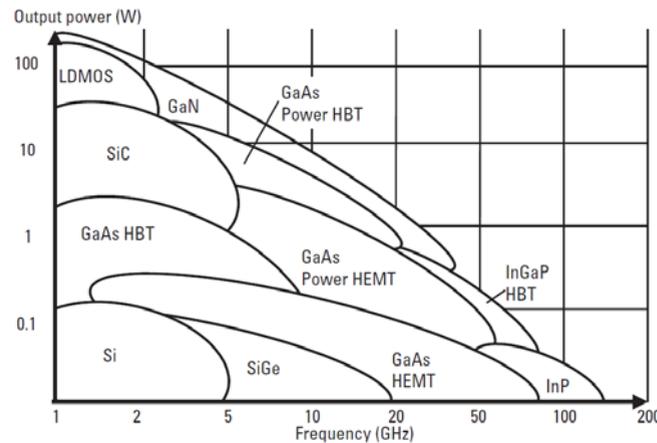

Fig. 1: Plot of output power versus frequency for various transistor technologies

2.1.1. Transistor Type

two basic types of active devices used in MMICs are the field effect transistor and the bipolar transistor. These can be in digital mode, or in analog mode (most MMIC applications), where small changes in the input signal are amplified between the other two connections. The types of FET include the metal semiconductor field effect transistor (MESFET) and the high-electron-mobility transistors (HEMTs). The types of bipolar transistor include silicon complementary metal-oxide-semiconductor (CMOS) transistors and heterojunction bipolar transistors (HBTs). These different transistor types are generally best suited to MMIC circuit types,as indicated in Table2.

Table 2: MMIC Circuit Types Best Suited to the Different Transistor Types

	CMOS	SiGe HBT	GaAs/ InP HBT	MESFET	HEMT
Oscillator	-			-	-
Mixer	-			-	-
Low-noise Amplifier	-			-	
Power Amplifier	-	-		-	
Switch	-	-	-		
Digital			-	-	-

2.2.   Field Effect Transistors

The top view of an FET, as if looking down onto the surface of an MMIC wafer, is shown in Figure 2. The current flows laterally across the surface of the wafer from the drain to the source and passes under the gate contact.
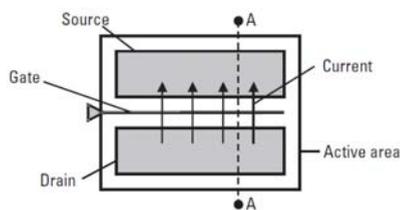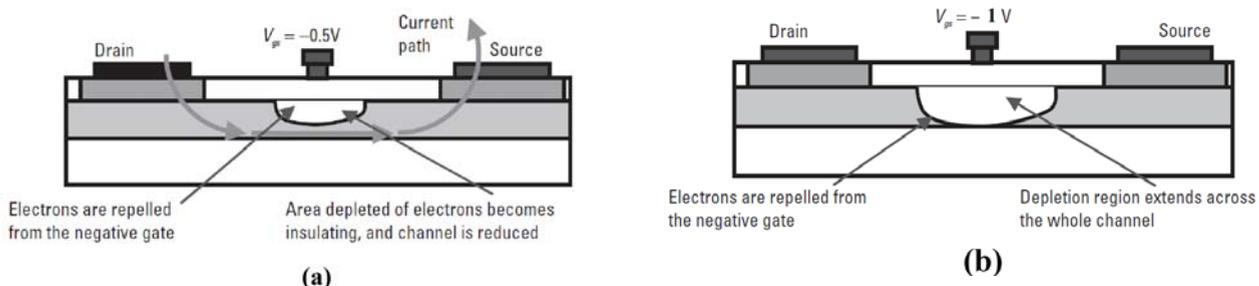

Fig. 2: Top view of a field effect transistor

The sectional view "A-A" of the FET in Figure 2 is shown in Figure 3. The FETs are formed with a low-doped layer of the semiconductor, which forms a conducting channel below the surface of the wafer. With no voltage on the gate, current can flow from drain to source. With a small negative voltage on the gate, current flow is reduced as shown in Figure 3(a). With a large negative voltage on the gate, current flow is stopped, and the transistor is switched off, as shown in Figure 3(b).

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Fig. 3: Sectional view of a FET with –0.5V on the gate (a), and –1.0V on the gate (b), relative to the source voltage.

- **MESFET**

The metal semiconductor field effect transistor (MESFET) is so called because gate contact is formed by a metal-to-semiconductor junction. If the semiconductor material is only low doped, the resulting Schottky contact between the gate metal and the semiconductor makes a very-low-leakage gate contact.

- **HEMTs**

The high-electron-mobility transistor (HEMT) operates like any other FET, except the channel is constructed from a junction of two different types of semiconductor material (known as a heterojunction) to give the free electrons in the channel higher mobility. For a GaAs HEMT, the other semiconductor material is

typically aluminum gallium arsenide (AlGaAs). the noise figure of the HEMT is much lower than that of ordinary FETs. An example HEMT LNA MMIC developed for a satellite receiver is shown in Figure 4. HEMTs are sometimes referred to in the literature as heterostructure FETs [4] or heterojunction FETs (HFETs) [5], but they are all high electron mobility field effect transistors (HEMTs) because they have a heterojunction between different types of semiconductors, which increases the mobility of the carriers in the channel.
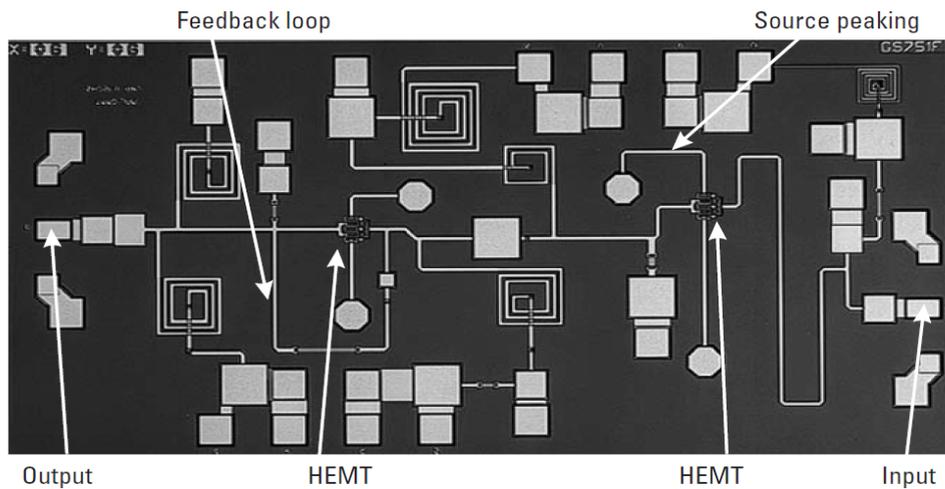
Fig. 4: A HEMT MMIC LNA

2.3. Bipolar Transistors

The top view of a bipolar transistor, as if looking down onto the surface of an MMIC wafer, is shown in Figure 5. The current flows down through the emitter and then laterally to the collector contacts.
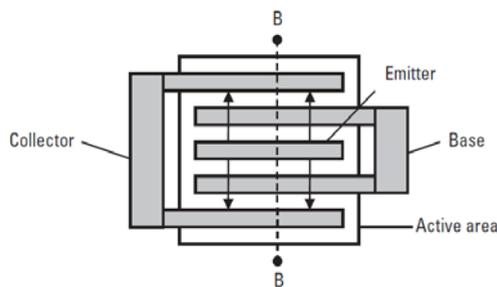

Fig. 5: Top view of a bipolar transistor.

• HBT

The heterojunction bipolar transistor (HBT) is similar to the standard bipolar transistor except that the base-emitter junction is usually a junction of two different semiconductor materials instead of the same material with different doping. Examples include HBTs fabricated with an AlGaAs emitter and a GaAs base, an InGaP emitter and a GaAs base, and an InP emitter and an InGaAs base. HBTs achieve the injection efficiency by the energy band-gap difference at the junction, which prevents holes from being injected into the emitter. This allows the base layer to be more heavily doped, which greatly reduces the base resistance, and this reduces the transit time of the device and increases its frequency response. Figure 6 shows an example of an InGaP HBT power amplifier operating at 5.8 GHz.

The SiGe HBT is different from standard silicon bipolar transistors because the base is constructed from a different semiconductor material, namely SiGe, creating heterojunctions with the silicon base and emitter layers. The SiGe base layer has a sloping concentration of germanium across its thickness, which creates an electric field to reduce the transit time of electrons moving from the base into the collector. This enables the SiGe HBT to operate at higher frequencies than silicon bipolar and allows silicon-based circuits to be considered for many microwave applications.
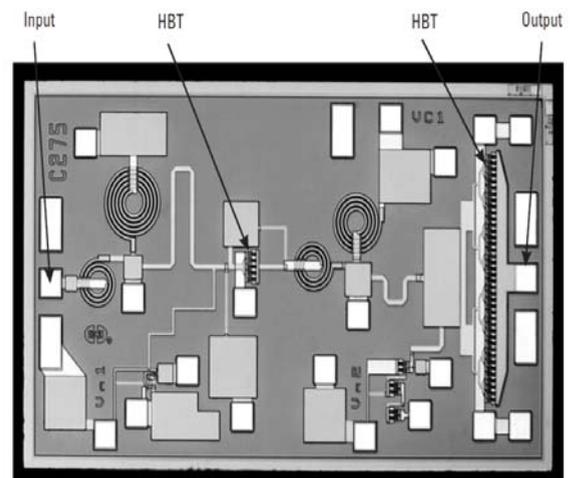

Fig. 6: InGaP HBT power amplifier operating at 5.8 GHz.

3. PASSIVE COMPONENTS
3.1 Diodes

Diodes in a MESFET MMIC process are generally created from the gate Schottky contact to the low-

doped semiconductor cap layer. In terms of their low-frequency $1/f$ noise, InP HBT diodes exhibit less noise than InP HEMT-based diodes, which is useful to note for oscillator and mixer applications.

3.2 Transmission Lines

The most common type of transmission line used in MMICs is called *microstrip*, which consists of a metal track on a dielectric substrate with an infinite ground plane on the back surface. The characteristics of a microstrip transmission line are determined primarily by the ratio of the track width to the height of the dielectric (*w/h*) because this is the main influence on the electric and magnetic field patterns.

3.3 Resistors

MMIC resistors are created either by using the active semiconductor layer under the surface of the MMIC or laying down thin films of resistive metal alloys above the surface as the resistive material. With both methods, the resistors are constructed with metal contact pads at either end of the resistive material film, as shown in Figure7, and have the characteristics of typical thin-film resistors.
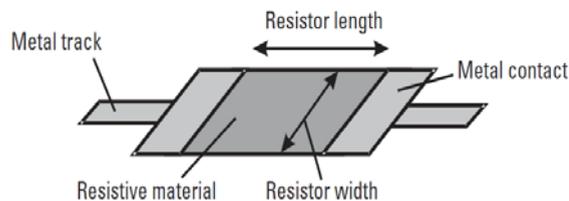

Fig. 7: Thin-film resistor construction.

3.4 Capacitors

MMIC capacitors are formed by two main methods: one uses the fringing capacitance between interdigital metal strips, and the other uses a metalinsulator-metal (MIM) sandwich. The interdigital capacitor, shown below in Figure 8, relies on the fringing capacitance between the long common-edge area of the metal fingers, which are separated by just a few microns depending on the minimum gap allowed by the foundry. These capacitors are usually formed using the same interconnect metallization as used for the transmission lines. This fringing capacitance is fairly low, so these capacitors are only able to reach capacitance values around 1 pF. However this capacitance value is relatively insensitive to process variations and can be a useful component at millimeter-wave frequencies.

The MIM capacitor, shown in Figure 9, can achieve much higher capacitance values because they are constructed of two relatively large plates of metal separated by a much smaller distance, and the gap in

between is also filled with an insulating dielectric material, which further increases the capacitance
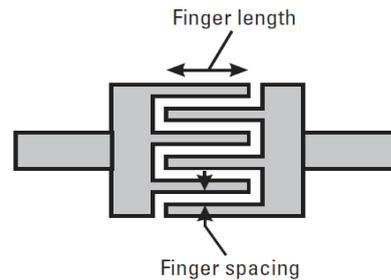

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Fig. 8: Six-finger interdigital capacitor as viewed looking down onto the wafer surface.
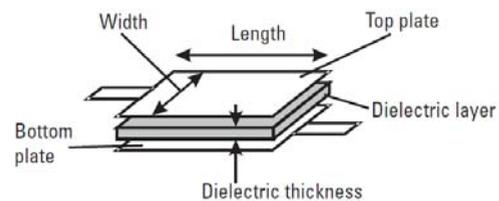


Fig. 9: MIM capacitor.

3.5 Inductors

MMIC inductors are fabricated using lengths of interconnect metal formed as narrow transmission lines, either on their own or wound around a central point to create a spiral transmission-line inductor. Spiral track inductors have more inductance than that due to their track length alone because the magnetic fields from each turn (or complete loop) of the spiral add up, creating a larger field through the middle of the spiral and mutual inductance between all the turns. Because of this, spiral inductors are a convenient way of generating a large amount of inductance in a small area of an MMIC chip. Many different types of spiral inductor are used in MMIC processes, ranging from square spirals, circular spirals, octagonal spirals, stacked spirals, to those that are in some way decoupled from the bulk substrate material.

4.   THE S-PARAMETERS

The concept of scattering parameters, or *s*-parameters, is to give a clearer and more straightforward understanding of the power relations between circuit elements connected through a multiport network. In other words, *s*-parameters give a more physical meaning to how a signal is scattered when it is incident on a circuit in terms of how much of the signal power is reflected and how much is transmitted out from the other ports of the circuit.

The *s*-parameter representation of an arbitrary circuit is called the scattering matrix, and the scattering

parameters can be understood by considering the incident, reflected, and transmitted signals in terms of traveling waves. MMIC foundries characterize the individual components' elements, such as capacitors, resistors, and spiral inductors, based on *s*-parameter measurements of the actual elements fabricated on characterization wafers. To do this, the foundry designs a mask-set that includes multiple geometries of all the different types of components from the passive devices through to the active transistor devices.
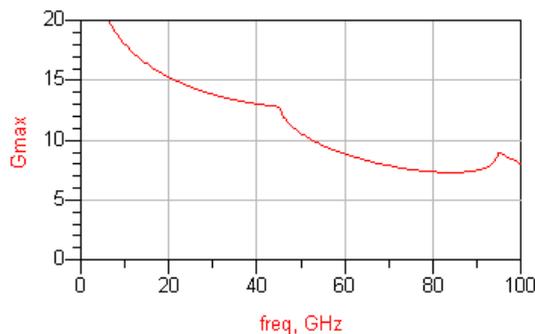
5. GAIN AND NOISE FIGURE

The maximum gain (G_{max}) and minimum noise figure (NF_{min}) of the typical MMIC transistor biased at 2.7V V_{ds} and 30% Idss is plotted in Figure 10. It can be seen that unconditional stability is exhibited across the entire of E-band (The worldwide availability of a large amount of spectrum at 71 -76 GHz and 81-86 GHz). Potential instability is apparent above and below the operating band and the amplifier design must incorporate circuitry to ensure stability in this region. It can also be seen that the G_{max} across E-band is only around 7dB [6].
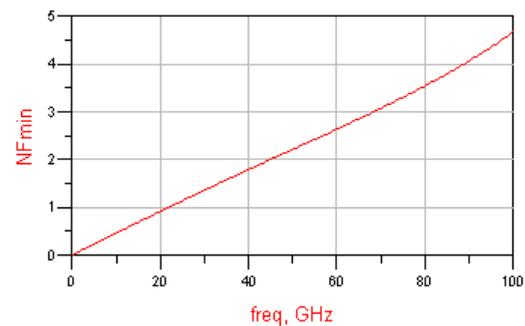

Fig. 10: Simulated G_{max} and NF_{min} for transistor biased at 2.7V Vds, 30% Idss

6. CONCLUSIONS

The initial impetus for development and growth of an entirely new and exciting microwave field was a response to the needs of new military systems under development [7]. The design of MMICs is essentially the same as that for most microwave components: one or more signals must be coupled onto the chip efficiently, then functions are performed on the signals, after which they are then coupled out of the chip and back into the system. the efficient coupling of signal power requires that the impedance of the signal source match that of the chip. In fact, to pass the signal efficiently through the whole chip, the impedances of the transmission lines, the active devices, and the system it sits in must all be matched. MMIC design is founded on impedance matching and control across the frequency range of interest. *Gain* and *Noise Figure* of a typical transistor is decreased and increased in terms of frequency increase, respectively.

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