The Developments in Low Noise Receiver Technologies

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During the late 1970's the Low Noise Amplifier (LNA) designs were based on silicon bipolar transistors. However ultra low noise receiving systems employed mainly solid state masers, cryogenically cooled parametric amplifiers and schottky diode mixers. In the 1980's the schottky barrier type Field Effect Transistors (FET) made of Gallium Arsenide (GaAs) became commercially available and quickly gained popularity. This device known as GaAs MESFET showed performance far superior to the bipolar transistor. The electron mobility of GaAs is 5 to 7 times that of silicon (1). GaAs MESFET's provided lower noise, higher gain and high frequency characteristics previously unavailable from bipolar transistors. GaAs FET technology, combined with cryogenic cooling made the noise performance of GaAs FET LNA's competitive with the performance of parametric amplifiers. Noise figures of GaAs FET's increases much more slowly than that of bipolar transistors. At frequencies above 120 GHz superconductor-insulator-superconductor (SIS) junction mixers demonstrated the best noise performance. Above 1 THz cooled schottky diode mixers provided the lowest noise temperature.

High Electron Mobility Transistor (HEMT)

Improvements on the GaAs MESFET with a heterojunction resulted in the introduction of High Electron Mobility Transistors (HEMT). A heterojunction is the boundary between two layers composed of materials with different band gaps, a band gap being the energy difference between the valance band and the conduction band of a semiconductor. Added to the basic MESFET structure is a heterojunction consisting of an n-doped AlGaAs schottky layer, an undoped AlGaAs spacer and then undoped GaAs channel. The key to HEMT's improved performance resides in the underlying semiconductor material. The silicon donor items reside in the HEMT's Aluminium Gallium Arsenide (AlGaAs) layer. Because of the conduction band discontinuity between high band gap AlGaAs and the undoped GaAs, the electrons are localized to a thin (<100 °A) two dimensional electron gas (2-DEG) layer on the GaAs side of the AlGaAs / GaAs interface. Since there are no donor atoms intensionally present in the undoped GaAs layer, the electrons in the 2-DEG layer do not undergo impurity scattering and hence exhibit high mobility and velocity resulting in a device with much higher channel mobility than a comparably doped GaAs FET. This material structure also gives HEMT's higher sheet carrier density and higher electron saturation velocity. Due to these properties the HEMT has higher transconductance (g_m) and lower noise figure than GaAs MESFET with comparable gate lengths.

Pseudomorphic HEMT

Low temperature performance of the HEMT's is somewhat complicated by the formation, at low temperatures, of deep electron traps (the so called DX centers) in the $Al_xGa_{1-x}As$ layers where, $x \geq 0.2$. This leads to collapse of the drain Current – Voltage (I-V) characteristics (2). To circumvent this collapse problem, Indium Gallium Arsenide (InGaAs) was used as the low band gap or 2-DEG channel material instead of GaAs. Because InGaAs has a lower band gap than GaAs, a lower Al mole fraction ($x = 0.15$) can be used in the AlGaAs while still maintaining the necessary conduction band discontinuity (approx. 0.3 eV) for a very high sheet carrier density. The increased mobility of indium with respect to GaAs increases the band gap discontinuity and therefore the number of carriers in 2-DEG. It became clear by 1986 that this GaAs HEMT's with pseudomorphic InGaAs channel provided improved microwave performance, including reduced noise and increased power added efficiency (3). These GaAs pseudomorphic HEMT's (pHEMT's) typically contain InGaAs channels with indium content ranging from 15 to 25%. pHEMT based LNA's are widely used for cellular mobile and radio astronomy applications. Agilent Technologies, San Jose, CA, USA, have developed a range of low cost surface mount plastic package pHEMT's which can be used at frequencies down to about 100 MHz (13). These pHEMT's have very high Third order intercept point of the order of + 36 dBm and 1 dB compression point of + 20 dBm. This means that the Spurious Free Dynamic Range (SFDR) of the amplifier is around 120 $dB.Hz^{2/3}$ assuming 30 dB gain for the two stage amplifier. In other words two tone signals of the order of - 30 dBm at the input of the LNA will give rise to the third order inter-modulation products of the order of - 100 dBm referred to the input. Recently a 500 - 900 MHz LNA has been designed using 800 μm gate width E-pHEMT ATF-54143 from Agilent Technologies. Microwave office design suite from Applied Wave Research (AWR) was used for design and simulation of the LNA. The simulated results yielded a noise temperature of around 15 °K at 500 MHz which increases to 23 °K at 900 MHz. The stability factor (K) was found to be around 10 ± 2 over the band. The prototype is being developed and the measurement results will be available soon.

InP HEMT

The InP based HEMT places an InAlAs / InGaAs heterojunction on an InP substrate. InP based HEMT's offer state of the art low noise and superior high frequency performance due to the intrinsic properties of the InAlAs / InGaAs material system where the high indium content (typically 53 to 80%) InGaAs channel posses high electron mobility and velocity and large conduction band discontinuity at the InGaAs / InAlAs heterojunction. This permits high 2-DEG densities to be obtained resulting in high current and transconductance (4). Typical 0.1 μm gate length InP low noise HEMT's exhibit g_m of 800 to 1000 mS/mm compared with 600 mS/mm for comparable GaAs pHEMT's. Typically InP HEMT's offer a noise figures of the order of 0.2 dB at 18 GHz which increases to 1 dB at 94 GHz. The minimum noise figure is obtained at a much lower drain bias voltage of 1 Volt compared with 2 to 2.5 Volts for a typical GaAs pHEMT. The minimum noise figure of HEMT's and GaAs MESFET's follows a frequency dependence

$$F_{min} = 1 + mf$$

Where,

f – Frequency in Hz

m is a constant which usually ranges from 0.02 to 0.06 ns and depends on the transistor material and dimensions. For frequencies at which $mf << 1$, F_{min} in dB is approximately equal to 4.34 x mf (5). Minimum noise figure is obtained when the transistor input is connected to the optimum source impedance Z_{opt} The value of Z_{opt} changes with frequency and usually moves counter-clockwise around the smith chart as frequency increases (5). InP HEMT technology does not suffer from carrier freeze-out effect at low temperatures because the electrons reside in the quantum well of the energy below the donor levels in the high band gap material. Sufficient carrier densities for high gain microwave operation can be maintained even at temperatures as low as 15 °K. Variety of high performance InP HEMT LNA's have been reported at frequencies ranging from 500 MHz to 215 GHz (6). These include both Hybrid Microwave Integrated Circuit amplifiers based on discrete transistors as well as Monolithic Microwave Integrated Circuits (MMIC).

Metamorphic HEMT

GaAs substrates offer several advantages over InP substrates. They are less fragile, cheaper and have superior crystal quality. GaAs substrates are more suitable for large scale MMIC production. GaAs wafers are available in large sizes of upto 6 inches. This superiority of GaAs over InP has lead to active research into suitable pathways toward employing GaAs as a substrate for InAlAs / InGaAs devices. One way to avoid InP substrate is to use Metamorphic buffers to accommodate the lattice mismatch between the GaAs substrate and active InAlAs / InGaAs heterostructure (7). Using the metamorphic buffer concept, lattice–matched modulation–doped InGaAs / InAlAs quantum well structures are grown on a strain-relaxed quaternary AlGaAsSb or InAlGaAs buffer on GaAs substrates. This structure called metamorphic HEMT demonstrated promising performance. This way it is possible to combine some of the good properties of InP or GaAs based processes. High indium content provides more gain and low noise. But low indium content is suitable for high break down applications such as power amplifiers (8). The MMIC group at California Institute of Technology (Caltech) have recently developed 0.6 to 1.6 GHz mHEMT LNA with a

Table -1

Lg (µm)	NF_{min} (dB)	Frequency (GHz)	Note	Reference
GaAs MESFET's				
0.3	0.4	1	Agilent ATF-10170	Datasheet
0.3	0.6	2	NE76038	Datasheet
GaAs HEMT's				
0.1	0.3	10		(11)
0.1	0.51	18		(11)
0.1	1.9	40		(11)
0.25	0.7	18		(11)
GaAs Pseudomorphic HEMT's				
0.13	0.31	12		(11)
0.13	0.45	18.		(11)
	0.22	1	Agilent ATF-54143	Datasheet
InGaAs / InAlAs on InP HEMT's				
0.1	0.8	60		(11)
0.15	0.4	10		(11)
0.2	0.48	10		(11)
0.2	0.8	26		(11)
InGaAs / InAlAs on GaAs HEMT (Metamorphic HEMT)				
0.1	0.25	12		(11)
0.15	0.24	12		(8)
0.15	0.61	36		(8)
GaN HEMT's				
0.15	0.6	10	SiC substrate	(11)
0.18	1.1	18	Sapphire Substrate	(11)
0.25	0.8	10	SiC substrate	(11)
0.25	1.05	18	SiC substrate	(11)

low noise temperature of the order of 15 °K (9). The LNA uses 1200 μm gate width and 0.15 μm gate length mHEMT manufactured at WIN (Wireless Information Networking) Semiconductors, Taiwan. mHEMT MMIC based LNA's operating at 220 GHz were reported recently (10).

GaN HEMT

It is also worth mentioning that Gallium Nitride (GaN) is presenting itself as a new and attractive option for fabricating the HEMT. The biggest benefit is for power amplification (11). They also offer low noise figures comparable with GaAs based HEMT's. The thermal conductivity of GaN HEMT's is lower, therefore GaN devices are built on substrates such as Silicon Carbide (SiC). The wide band gap of SiC results in both high mobility and high breakdown voltage. GaN HEMT's With gate length of 0.15 μm yielded a noise figure of 0.6 dB at 10 GHz (12).

Table – 1 gives a comparison of minimum noise figures at room temperatures for the state of the art in various material structures for GaAsFET's and HEMT's. The device gate length, minimum noise figure, frequency of measurement, comments about the data and reference are listed, respectively.

Finally, we add few points regarding the design of LNA's for VHF, UHF and Low microwave frequencies. At VHF and UHF frequencies pHEMT's are the right choice for designing the LNA's. For low microwave frequencies mHEMT's and InP HEMT's can be considered for LNA design. For these frequencies the method of combination of source inductive feedback and drain resistive loading ensures LNA's low noise performance while meeting good power match and circuit stability requirements. The source inductance acts as series feedback to the device. The amount of series feedback has a dramatic effect on in-band and out-of-band gain, stability and input return loss. The source inductance value has to be optimized. Excessive values of inductance will lead to out of band high frequency gain peaking and resultant oscillations. Generally the conjugate match (tuning for lowest VSWR) does not coincide with the optimal noise match. The use of source inductance effectively moves the input conjugate match closer to the optimum noise match.

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