From December 2006 *High Frequency Electronics*

InP Provides Improved Low Voltage Wireless PA Performance

By Michael Gaynor
Antenova

Indium phosphide (InP) offers a performance improvement at lower operating voltages, compared to today's well-established gallium arsenide (GaAs) semiconductor technology

Is history about to repeat itself in the wireless power amplifier industry with indium phosphide (InP) replacing the now dominate gallium arsenide (GaAs) semiconductor material just as GaAs replaced silicon for power amplifiers in the 1990s? There are a few companies that are currently exploring this avenue by commercializing InP for the wireless industry. InP is not a new technology. It is currently utilized in military and photonics with thousands of wafers fabricated per year. However, this pales in comparison to GaAs with high volume ODM fabs pushing a hundred thousand or more wafers each year. Smaller ODM fabs are not at this level, but, total GaAs wafer quantities are approaching a three orders of magnitude multiple of the total InP wafers fabricated in one year. However, a similar story was conveyed/disseminated by the GaAs industry at the end of the twentieth century with regards to silicon as the incumbent. It mainly took a disruptive battery technology change and one major cellular phone Original Equipment Manufacturer (OEM) buy in to enable GaAs as a replacement for silicon. A similar scenario is currently occurring opening a window of opportunity for InP. The advantages and performance of InP devices at Xindum Technologies will be explored as suited for the commercial wireless power amplifier industry.

In the 1990s the cellular portable manufacturers were happy with silicon. It was a low cost material with acceptable performance. These were the days of mainly analog FM phones with GSM starting to appear. The batteries were 5 cells of nickel cadmium (NiCd) that have a cell voltage between 1.2-1.6 V. End of life for the five cell battery pack was 5 × 1.2 = 6 V. This was fine for silicon, but with the emergence of digital schemes and the demand for longer talk time, battery technology was refined. There is also a memory effect with the NiCd batteries that requires reconditioning by deeply discharging the battery and fully recharging a number of times. Typically, the NiCd batteries were rendered useless after a few hundred or thousand charging cycles. The two technologies that emerged as replacements were nickel metal hydride (NiMH) and lithium ion (Li Ion) with fuel cells and zinc air losing favor. The NiMH was advantageous as almost a direct replacement of NiCd with its cell voltages of 1.2 to 1.5 V. It enjoyed the advantage of no memory effect like NiCd. However, the Li Ion was a new beast. The cell voltages were much higher, 4 V, but, the higher energy density made these a sought after technology. There was just one problem for a two cell approach to meet the higher voltages demanded by silicon. The cells had to be balanced during charging and discharging. Additional circuitry was required to balance the charging and discharging of the two cell approach to avoid fires due to the pyroelectric lithium material. Along came the savior, GaAs, that could operate from just one Li Ion cell while meeting power and linearity requirements for the new digital modulation technology, and the industry took notice. A small start up company in North Carolina offered GaAs power amplifier technology and became a large billion dollar company today.

Conventional InGaP Power Amplifier Comparison						
Application	Mode	Frequency	Specification	InP	InGaP	conditions
Quad Band dual mode	EDGE	850/900 MHz	PAE at 29.0 dBm	30%	25%-27%	2%-3% RMS EVM
		1710/1910MHz	PAE at 28.0 dBm	33%	25%-27%	and -58dBc - -60dBc ACLR at 400kHz
	GSM	850/900 MHz	PAE at 34dBm	50.0%	49.0%	
		1710/1910MHz	PAE at 32dBm	54%	51%	
WCDMA	full pwr	region 5	PAE at 28.5dBm	45%	40%	ACLR1/2=-40dBc/-58dBc
	backoff		16dBm-28.5dBm range	35.0%	20.0%	
	backoff		16dBm only through switching	40%	35%	
	low supply		2.5V battery	>26dBm & 43%	N/A	
CDMA	full pwr	IS95	PAE at 28.5dBm	40%**	40%	ACLR1/2=-50dBc/-60dBc
WiMax		2.5Ghz	PAE at 22dBm	25%*	12%-16%	

* at 3.3V supply voltage for InP versus 4.5V or higher for GaAs
** as dual mode with WCDMA

Table 1 · InP performance versus InGaP for various wireless applications.

This is the past and soon forgotten history, and now the same arguments that were waged by the silicon industry against GaAs are now being waged by the GaAs industry against InP. The main arguments are: it is too expensive, it is immature, it is fine for military but not for high volume commercial usage. Three factors need to be enabled for InP to appear in the wireless industry. The first is cost, the second is another disruptive technology influence, and the third is acceptance by one industry driver.

The same disruptive factor of lower battery voltages that helped GaAs become mainstream is about to occur again in the cellular phone industry. The consumer demands of increased talk time, multi-media, and more functionality in the cellular phone have pushed the current Li Ion batteries to their limits. New higher energy density batteries based on Li Ion are on the horizon, but they reduce the operating cell voltage to 2.7 V. InP promises to be a parody of the GaAs story with new battery technologies for higher energy density expected in 2007. The lower voltages of these new higher energy density battery cells will create an opportunity for InP with its superior performance at low voltages.

The advent of the new higher energy density batteries leaves three options for the cellular and other wireless portable applications. The first is to use two cells with balanced charging systems and increased battery supply voltage over the current Li Ion single cell technology. This is a hard sell to the cellular phone industry due to the breakdown voltages of GaAs. In addition, the trend in the other cellular electronics is to reduce the operating voltage leaving a wider gap between the PA voltage and the other cellular phone circuitry. The second option is to add a DC/DC converter for the PA. It is expected that this will be done initially with GaAs power amplifiers. The third option is to include another disruptive technology like InP to work directly with the disruptive battery technology single cell voltage. This is advantageous since no DC/DC converters will be required in the cellular phone. The 1.8 V transceiver technology can run through a low cost small LDO. The digital logic may utilize a DC/DC with its 1.2 V technology, or it can also be supplied through an LDO. The PA can run directly from the battery and does not require an expensive DC/DC converter due to the high current drain of this converter versus the lower current drain of the present cellular phone DC/DC converters for digital logic and transceiver chips. Also these existing DC/DC converters for digital logic and transceivers are step down converters so the input current is less than the output current. The PA DC/DC converter would require a step up converter (boost) that pulls more current from the input or battery than the output or PA current.

The basis of comparison is now GaAs for cellular portable phone power amplifiers. A table of InP versus GaAs is given (Table 1), however, some explanation is needed to judge InP against GaAs from this table. First, the InP parts that achieved the performance in this table were not optimized for these applications. These parts were designed for initial power capability and not linear performance. These parts were a step in the procedure to size the parts for power. The next phase will refine the MMIC designs and start optimizing for particular applications. In the EDGE and GSM comparison section of the table, these results for InP are a compromise for the match between EDGE and GSM performance. The EDGE only performance is greater than 40% when ignoring GSM during tuning versus 35% for GaAs. More work could be done to achieve a better compromise between GSM and

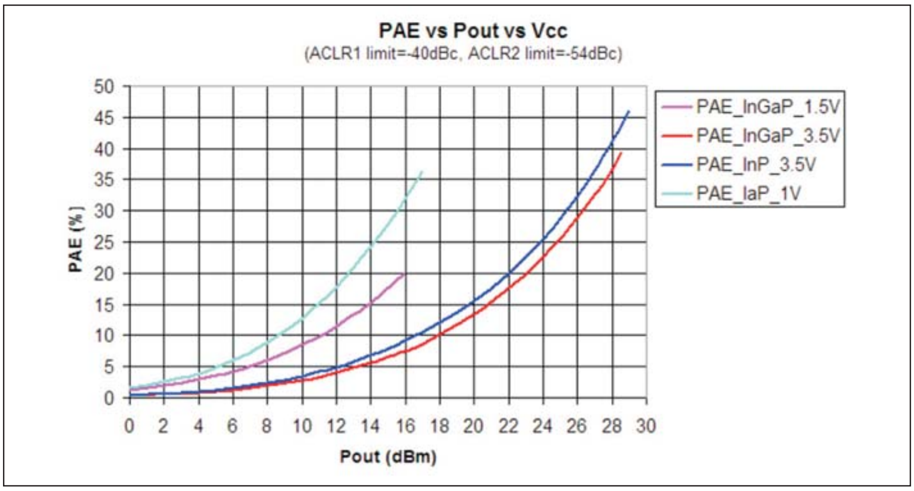


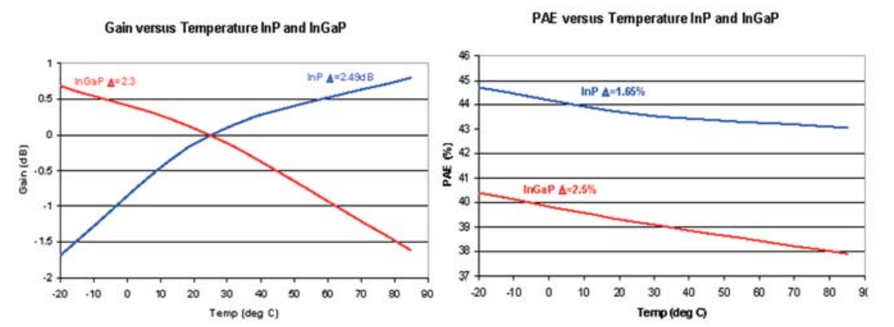
Figure 1 · InP versus InGaP for WCDMA amplifier.

EDGE performance. In the past, we were capable of achieving 29% for EDGE highband and 28% for EDGE lowband with an accompanying 53% for GSM highband and 57% for GSM low band with GaAs. We could use similar techniques for InP to achieve better EDGE and GSM combined performance. However, the data in the table for GSM and EDGE with GaAs is from a high volume product of an industry leader in GaAs power amplifiers.

The WCDMA data in the table requires the most explanation and some more data for a fair comparison. As discussed above, InP performs best at lower voltage and mates well with the new lower voltage higher energy density battery technology. However, WCDMA products have employed a DC/DC converter in their topology. There are a number of techniques for reduced power and voltage conditions. The optimum for the system is to adjust the DC/DC converter in an analog fashion as the power is reduced. This creates a power phasing nightmare at the OEM to calibrate and store many power control values. Typically a compromise is reached where either two or four power levels are calibrated. In the case of four power levels, a DC/DC converter is used and the output voltage of the DC/DC converter is adjusted in four discrete value steps. The power control scheme lowers this voltage as the RF power requirements are reduced thus maintaining good overall power added efficiency from the PA and DC/DC converter system and hence battery life. In the case of only two steps, this is typically done in the PA only. There are three techniques: bypass the final stage with a switch, incorporate another smaller PA chain without the final device and switch it in place, or switch additional components into the matching network to change the impedance match or load. The final device is switched out as the power is reduced beyond a trip point, typically 16 dBm. These designs are different and should not be compared against each other. In the case of only two steps, nearly the same PAE is achievable at the low power step as at the full power step, 45%. This is compared to 30% for current state of the art InGaP technology. In the case of the DC/DC converter and multiple steps, InP technology can achieve 35% PAE at 16 dBm whereas current state of the art InGaP only achieves 20% PAE at this power level. Data for a two stage InP power amplifier sample is compared with a commercial InGaP amplifier in Figure 1. This InP amplifier achieves 17 dBm for a 1 V supply voltage while meeting ACLR performance. The voltage could be slightly reduced for a 16 dBm output with 35% PAE and ACLR performance. This is a 1.75x improvement in the InGaP performance at 16 dBm. In addition, the InP amplifier only needed two stages to meet the gain requirements. This has advantages in the noise performance since a three stage InGaP amplifier exhibits too much gain and feedback or loss is added to the first stage to reduce gain and control stability. This loss directly impacts the noise figure of the amplifier.

Another distinct advantage of InP over InGaP for WCDMA is the low turn on voltage. InP enjoys a low 0.45 V turn on voltage. This reduces the reference voltage threshold to only two base emitter voltage drops or 0.9 V. In practice, 1.2 V is alloted for temperature, make tolerance, and resistor drops. This is compared to the 1.2 V turn on for InGaP parts. Two base emitter voltage drops plus temperature shifts, make tolerance, and bias circuit resistor drops causes the reference voltage threshold to increase dangerously close to 2.7 V. Much effort has recently been expounded to reduce this turn on voltage by as little as 0.1 V to avoid starving the device over the operating temperature limits [1].

One last advantage seen for InP in the WCDMA amplifier sample is its thermal performance. The two stage WCDMA amplifier was tested over temperature with the results in Figure 2. The gain deviation from 25°C performance and the PAE are compared to a commercially available amplifier in the graphs. This is an unfair comparison for InP since the InGaP amplifier employed temperature compensation in its bias circuitry whereas the InP amplifier had none. Even without temperature compensation bias circuitry, the InP amplifier performs as well as the InGaP amplifier over temperature. A flatter response over temperature could be obtained with InP and tem-



Temp.:	-20 deg	
Vcc	Pout	PAE
3.4	28.5	44.71%
3.4	16	10.03%
2.5	26	45.50%
2	24	44.60%
1.5	21	41.63%
1	16	33.22%

Temp.:	85 deg	
Vcc	Pout	PAE
3.4	28.5	43.06%
3.4	16	8.25%
2.5	26	43.83%
2	24	43.42%
1.5	21	39.26%
1	16	29.41%

Temp.:	25 deg	
Vcc	Pout	PAE
3.4	28.5	43.61%
3.4	16	8.91%
2.5	26	44.51%
2	24	44.08%
1.5	21	40.38%
1	16	31.41%

Figure 2 · InP and InGaP WCDMA PA performance over temperature.

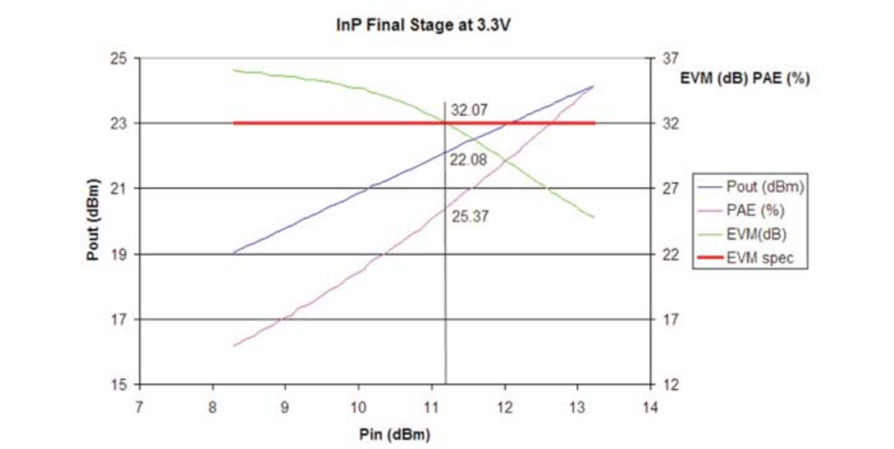


Figure 3 · InP WiMax final stage performance.

perature compensation, however, the positive temperature coefficient InP amplifier could be mixed with some negative temperature coefficient GaAs stages to develop a flat overall line-up response with temperature. Some applications require these type of techniques and in the past thermal attenuator pads were employed [2].

InP has also been applied to WiMax for the new mobile WiMax application. In this application, the power amplifier will not enjoy the higher operating voltages of 4.5 or 5.5 V, but must work at 3.3 V. Most InGaP products to date only achieve the 2.5% EVM, 32.04 dB, requirement for 4.5 V or higher. A sample InP final stage amplifier is capable of 2.5% EVM at 3.3 V and 22 dBm of output power with 25% PAE. In comparison, the best performance InGaP amplifier only delivers 21% PAE at this power and EVM, but requires 4 V to achieve it. In addition, it is not in high volume production. At 3.3 V, the EVM drops to 4.5% but the PAE improves to 25% for the same power output. Most commercially available WiMax amplifiers exhibit PAE performance between 10% and 16% at 2.5% EVM, and they require 4.5 V.

This performance improvement combined with high breakdown voltage has started to gain the attention of the industry. One PA module supplier has recently verified our breakdown voltage through extensive testing. Although others are looking to commercialize InP, we differentiate ourselves with high breakdown voltage capability, 21 V. This breakdown voltage is achieved with increased RF performance over current state of the art InGaP power amplifiers as discussed above. This has many players in the industry considering or reconsidering InP for cellular and wireless power amplifiers.

Up to now in this paper we have demonstrated performance capability, but we have not addressed the third enabling factor for InP of cost. The new lower voltage high energy density battery technologies were discussed as the main enabler for InP, but the industry will not adopt it unless the cost is in-line. This is a divergence from the GaAs parody where GaAs could demand a slightly higher price initially with adoption by the industry to help build the demand. InP does not have that luxury to demand a much higher price or industry will not adopt. They will find another solution like current GaAs parts and a high power DC/DC boost converter. The industry will not adopt InP regardless of the performance improvements without the cost in-line with current solutions in volume. Recently the supply chain has added new sources for starting InP wafers to address the cost factor. This is key to cost, since the processing of the InP wafers is the same as GaAs. This has been confirmed with another GaAs fabrication power amplifier supplier that tried InP but could not achieve the high breakdown voltage demanded of cellular power amplifiers. With processing the same cost as GaAs, and power density higher for InP, the only detrimental cost factor is the starting material. Until recently, there was only one main supplier for the starting InP wafer that demanded a high price. There are now five known suppliers with prices of starting material approaching the cost of GaAs wafers in low volume. These are currently four inch wafers similar to current GaAs four inch wafers. These come from China which is the world's leading supplier of indium, as a by-product of the electrolytic refining of zinc and tin. China currently utilizes its indium reserves in the semiconductor industry in the form of indium-tin-oxide thin films in the manufacturing of Liquid Crystal Displays and in the form of aluminum indium gallium phosphide (AlInGaP) and indium gallium nitride (InGaN) for light emitting diodes (LEDs). AlInGaP is used to create red, orange, and amber light; while InGaN is used for green, blue-green, blue, white, and ultraviolet (UV) light.

With performance demonstrated and industry driver of lower voltage batteries and cost reducing the last remaining issue is reliability and ruggedness. The standard 1,000 hour HTOL testing has not been done to date on the wireless application HBT, but the industry has been reliably producing InP HBT amplifiers for photonics and military applications. In addition, the InP wireless device structure is similar to the current high yielding and high volume InGaP HBT devices. Furthermore, InP uses the same process steps as GaAs fabrication with only differences in the backend processing. The backside substrate via process requires the brittle InP wafer to be thinned to a minimum of 100 µm. In contrast, GaAs devices have been thinned to 50 µm. These backend differences can be eliminated by using the Cu pillar approach [4]. Cu pillars not only eliminate the differences, but have advantages of lower cost through elimination of the costly backside via process, smaller die size through elimination of large via, elimination of die backgrind. Wafer thinning is not required since the majority of the heat removal for flip chip with Cu pillar is through the thermally conductive Cu pillar.

The performance of InP has been shown with advantages for lower V_{ref} in WCDMA applications allowing for direct connection to the DAC instead of through the power management IC, lower operating voltage capability with the capability to meet full WCDMA power and linearity requirements at 2.7 V, high breakdown voltage above 20 V capability, and increased performance under increased thermal conditions. In addition, InP may be advantageous for the polar modulation techniques being utilized for high data rate digital modulation applications. An example is EDGE where the peak to average ratio exceeds 3 dB while the minimum to average ratio exceeds 12 dB. The improved low voltage performance of InP, higher efficiency and linearity below 1 V, offers a distinct advantage. Even at full power, the supply to the power amplifier is subject to low voltages to cover the nulls or minimum levels in the modulation under EER or polar modulation. One last advantage for InP is its higher maximum frequency of oscillation or f_{max}. This leads to higher operating frequencies for amplifiers and more available gain at lower frequencies than f_{max}. Could the upcoming application of collision avoidance radar become the first to adopt InP in a high volume market space? It appears that the three factors of cost, disruptive technology influence, and acceptance by an industry driver are coming to fruition and giving InP an opening into the wireless arena.

References

1. P. J. Zampardi et. al., "Demonstration of a Low Vref PA Based on InGaAsN Technology," *2006 IEEE Radio and Wireless Symposium, RAWCON,* IEEE Topical Workshop on Power Amplifiers for Wireless Communications workshop, January 17, 2006.

2. Michael P. Gaynor, *System in Package: RF Design and Applications,* Artech House, October, 2006.

3. John D. Jorgenson and Michael W. George, "Indium," U.S. Geological Survey report 2004-1300.

4. Triquint Semiconductor, "A High Performance GSM Quad-band PA Module with Breakthrough Size reduction," *Microwave Journal,* April, 2005.

Author Information

Michael P. Gaynor is a Technical Director for Antenova. He is responsible for RF circuit and system architecture design mainly in System in Package (SiP) solutions. Mike recently joined Antenova with a prior history including Xindium, CEL, Amkor, and Motorola. He designed many RF SiP products for industry leaders while at Amkor. He has 20 years experience in RF/Microwave product development with an emphasis on transmitter linearization. He received his BSEE from the Illinois Institute of Technology (IIT) in 1986 and his MSEE from IIT in 1993 with concentration in areas of communications and RF and Microwave design. He is a member of the IEEE and its Microwave Theory and Techniques Society, Eta Kappa Nu and Tau Beta Pi. He has numerous patents and publications, including a recent book titled *System-in-Package: RF Design and Applications.* He can be reached at mgaynor3@comcast.net