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GaN HEMT in class E power amplifiers:

Charging the wireless way

More efficiency, shorter time to charge, higher power density – those are the customer demands of semiconductor devices for wireless charging systems. A GaN HEMT can do the job in class E RF power amplifiers.

By Milko Paolucci and Peter Green

Wireless charging technology has existed for some time but only in recent years, with the proliferation of inductive wireless charging technology, become more widespread. But to make wireless charging truly ubiquitous and offer improved end-user convenience like improved freedom of positioning, it needs to evolve further, and likely will apply magnetic resonance technology over time. For the latter, high transmission frequencies (multiple MHz) are required and pose significant challenges to standard silicon power technologies within transmitter and the receiver devices.

In this article the authors introduce the benefits of GaN power devices in class E radiofrequency power amplifiers as used in wireless charging, highlight the advantages of GaN HEMT devices over MOSFETs in this power amplifier topology that is – besides class D – proposed for wireless power transfer according to the baseline specification of the Air Fuel Alliance.

Currently most wireless charging systems are based on the inductive (Qi) standard, operating by coupling at frequencies in the 100 to 300 kHz range. Although this is the more widely adopted approach, it allows charging of a single device only that needs to be placed very close to the charger in a specific orientation. Alternative topologies have gained increased attention – such as class E – to enable more free designs in wireless power transfer through resonant coupling. We have to note here that these topologies are not new, and are already used successfully in RF applications where the terminology "amplifier" is widely used to describe them. With these topologies high efficiency can be achieved in the range 1 to 10 MHz of operating frequencies. These power amplifiers are employed in the transmitter section of a wireless power system, as shown in Fig. 1.

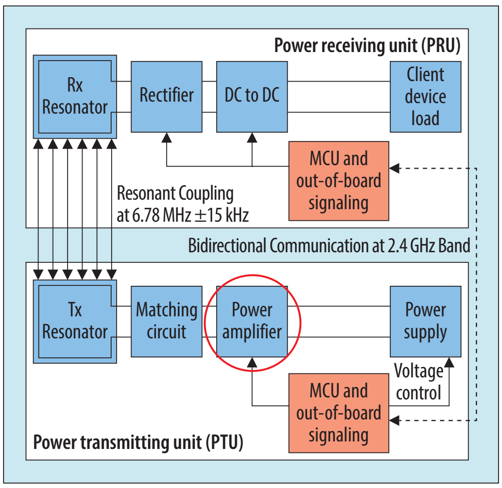

Fig. 1. Block diagram of a system for wireless charging consisting of receiver and transmitter unit.

(photos source: Infineon)

In resonant wireless charging, based on 6.78 MHz as proposed by the Air Fuel Alliance, resonant inductive coupling is used in which high-Q factor resonators enable power transfer over much greater distances using the much weaker magnetic fields in the peripheral regions. Thus, the resonant technology allows for a "drop and go" near-field charging experience, and offers considerable user experience benefits over inductive solutions.

Faraday's law states that an electric potential is generated by a coil of wire when the magnetic flux enclosed by it varies. In wireless power transfer an RF power amplifier drives a power transmitting unit (PTU) consisting of a coil in a tuned circuit to produce a varying magnetic flux. Tuned to the same frequency, also a coil in a circuit can be found in the power receiving unit (PRU), intersecting the magnetic field so that a voltage is induced.

This voltage depends on the rate of change of flux and number of turns. Output from the receiver coil is rectified and converted to the wanted level for the portable device being charged. Coupling depends on separation between the two coils, defined by the coupling factor *k*. A *k* of less than 0.5 represents a loosely coupled system as used in magnetic resonance coupling. Fig. 1 shows the system blocks of the PTU and PRU where microcontrollers with Bluetooth communication are used to request and regulate the amount of power transmitted as required by the devices being charged.

Why consider GaN for power applications including wireless charging? The merits of the relatively new GaN technology have already been proved in RF systems. Now, as significant improvements in its figure of merit (FoM) have been achieved, GaN is gaining attention for many power applications.

Fig. 2 shows the improvements presented by GaN technology compared to state-of-the-art silicon solutions from different vendors. The logarithmic scale helps to understand the quantum leap that GaN technology is offering, almost one order of magnitude for all FoMs.

Requirements of class E power amplifiers

The single-ended class E RF power amplifier topology consists of an RF inductor L1, which supplies an approximately DC current to the switching FET Q1, resonant circuit and load – as shown in Fig. 3. Q1 switches at 6.78 MHz with a fixed 50 percent duty cycle. When the circuit is tuned to the same frequency a half-sinusoidal voltage appears at the drain, which peaks at 3.56 times the DC input voltage V_{IN} and falls back to zero just before the start of the next switching cycle, thus operating with zero voltage switching (ZVS). The load impedance must be purely resistive to enable this. An impedance matching network is placed between the power amplifier and the transmit resonator designed to cancel out all reactive elements.

The values of L2, C1 and C2 are determined according to the resonant frequencies of the two switching states. When the switch is off, C1 in parallel with the drain-source capacitance of Q1 contributes to the higher resonant frequency. When it is on, the lower resonant frequency is determined by L2 and C2 only. For ZVS operation the switching frequency must lie between the higher and lower resonant frequency, and the sum of the periods of one half cycle of each resonant frequency must be approximately equal to the period of the switching frequency.

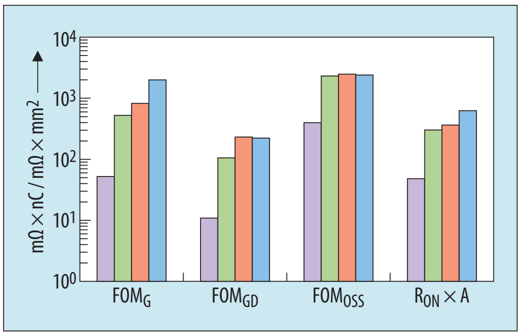

Fig. 2. FoM comparison of GaN (violet) and silicon (various providers shown in green, orange and blue).

If circuit resonance is higher than the switching frequency, the drain voltage rings to a higher peak, which can be up to seven times V_{IN}, and will fall to zero before the start of the next switching cycle so that body diode conduction occurs during the intervening period. If on the other hand the circuit resonance is lower than the switching frequency, the drain voltage will not be zero at the start of the next switching cycle. This creates hard switching with very high associated losses at 6.78 MHz.

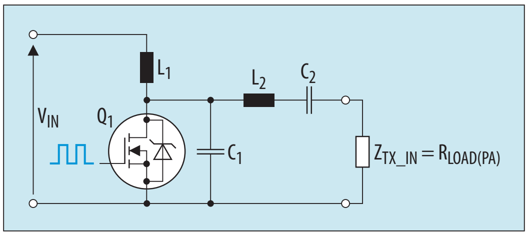

Fig. 3. Major elements of a single-ended class E RF amplifier.

To attain high power amplifier efficiency the circuit must be correctly tuned. In addition the output current should not be too high since this creates power loss in L2 resulting from conduction and eddy current losses due to the skin effect, which are significant at 6.78 MHz. The PRU and impedance matching network should then be designed to develop a high Z_{TX_IN} for the power amplifier load.

GaN technology also provides unique benefits for designs based on a class E power amplifier. One rated up to 16 W was tested using a BSC12DN20NS3 200 V, 125 mΩ OptiMOS 3 switch. To evaluate power amplifier performance and efficiency a resistive load was used and measurements taken at 25 Ω, 15 Ω and 5 Ω. Efficiency was measured at 91 – 92 percent in each case. The operating waveforms for 25 Ω are shown in Fig. 4. The red trace shows the drain voltage waveform. It is observed that the shape is not a pure half-sinewave, displaying a reduced slope at lower voltages, which prevents it from falling all the way to zero before the next switching cycle resulting in some hard switching. This effect is caused by the effect of the MOSFET C_{OSS} on the upper resonant frequency of the circuit. In silicon MOSFETs C_{OSS} increases considerably at lower voltages, which creates this distortion.

Although the circuit is able to operate with acceptable efficiency and the switching losses caused by the small amount of hard switching are not high, this is still problematic. The circuit has to be retuned, resulting in a higher peak voltage, which reduces the maximum power capability and output impedance range over which the power amplifier can operate without reaching the MOSFET avalanche rating BV_{DSS}.

A GaN HEMT with the same BV_{DSS} and $R_{DS(on)}$ ratings was also tested in the same circuit, the results are shown in Fig. 5. Fig. 6 compares COSS characteristics for the two power switch types plotted on a logarithmic scale, revealing that the increase in the GaN device is much less than in the MOSFET, though the data sheet value at V_{DS} of half BV_{DSS} is very similar.

The drain waveform for the GaN-based device is seen to be much more sinusoidal than in the MOSFET example. Hard switching is not present, and the peak voltage is equal to 3.56 times V_{IN}, indicating that the circuit is operating at a theoretical optimum. This allows operation over a wider range. Furthermore, in practice the circuit is easier to tune and less prone to drift caused by tolerance and temperature.

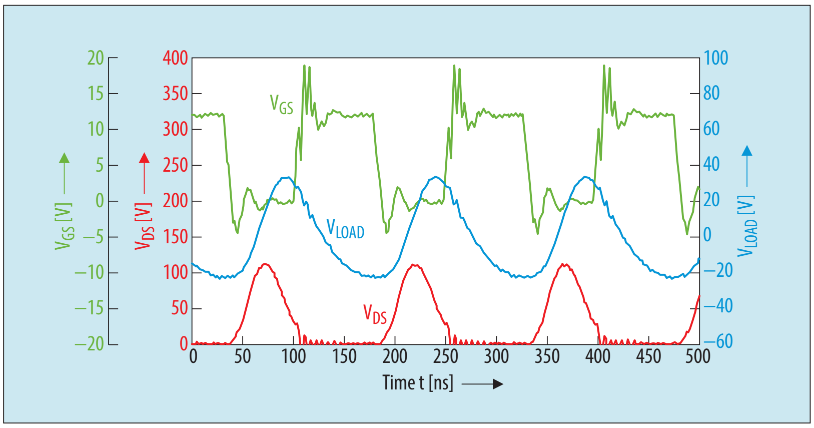

Fig. 4. Waveforms of a single-ended class E amplifier based on a silicon MOSFET.

Decisive GaN characteristics for wireless systems

The advantages of GaN devices in wireless power transfer can be summarized as follows:

Lower gate charge loss

GaN devices are typically driven with 5 V gate drive voltage as opposed to standard silicon MOSFETs typically driven around 10 V. The gate charge (Q_G) for the GaN device is about one fifth of that for a MOSFET or similar $R_{DS(on)}$ and V_{BRR}, which results in dramatically lower gate drive current and far lower losses in the gate driver IC. To minimize gate charge loss it is preferable not only to choose low Q_G, but also to use device technology with low gate threshold voltage, allowing the designer to use lower driving voltage, thus decreasing overall losses related to the driving circuitry.

Gate charge losses can be calculated as:

$$P_{GATE}=Q_{G\_SYNC} \cdot f_{SW} \cdot V_{dr}$$

Where Q_{G_SYNC} is the gate charge at voltage V_{dr} without the Q_{GD} (since a ZVS transition is assumed), f_{SW} is the switching frequency and V_{dr} is the driving voltage.

Body diode losses

Although GaN HEMT devices do not have an actual body diode like a MOSFET, they do exhibit a diode-like behavior. Another important source of system losses is the body diode forward voltage, which is in fact higher in GaN devices. In class E topology diode conduction is avoided by correct tuning of the circuit.

$$P_{DT}=U_{SD} \cdot I_{OUT} \cdot f_{SW} \cdot T_{DT}$$

In evaluation of body diode losses it is important to compute the correct V_{SD} value, which will vary with current and temperature.

Key factors of CoolGaN HEMTs from Infineon

Continuous growth of the world's population and acceleration of social development have led to an increasing demand for electricity, and the increasingly urgent environmental pressure forces us to do more with less energy. For years engineers have sought ways to improve circuit design using existing silicon-based semiconductors, constantly wringing more efficiency from designs. While this has clearly delivered some benefits, there are very few advances still left in this area and engineers are seeking other opportunities for efficiency. Since the beginning of solid-state electronics, silicon (Si) has been the material of choice for power devices. But a new generation of wide bandgap materials including silicon carbide (SiC) and gallium nitride (GaN) are entering the market, providing significant opportunities for power designers. These technologies are key for the next essential step towards an energy-efficient world by allowing for greater power efficiency, smaller size, lighter weight, lower cost – or all of these together.

Compared to silicon, the breakdown field of Infineon's CoolGaN enhancement (e-mode) HEMTs is ten times higher and the electron mobility is double. Both output charge and gate charge are ten times lower than with Si and the reverse recovery charge is almost zero, which is key for high-frequency operations. GaN is the suitable technology of choice in hard switching as well as resonant topologies, and is enabling new approaches in current modulation. Infineon's GaN solution is based on the most robust and performing concept in the market – the e-mode concept offering fast turn-on and turn-off speed. CoolGaN products focus on high performance and robustness, and add significant value to a broad variety of systems across many applications such as server, telecom, wireless charging, adapter and charger, and audio.

GaN devices are by nature normally-on devices, since the 2DEG channel is immediately present in a GaN/AlGaN heterojunction. The power electronics industry, however, strongly wishes normally-off devices. There are two ways to achieve that: the socalled cascode approach, or to realize a real monolithic enhancement mode device. Infineon is focusing on the e-mode GaN concept for its CoolGaN 400 V and 600 V devices, suitable for all consumer and industrial applications.

The reduced switching losses associated with GaN deliver smaller and lighter designs. On the one hand, the SMD packaged device allows compact and modular designs, while secondly, smaller heatsinks and less components can be used. And thirdly, moving to higher switching frequency in certain applications (when required) reduces the size of the passives. At system level, higher power density achieved by GaN-based power supplies allows more computing power to be installed within the same volume.

To support accurate lifetime prediction Infineon has developed a highly structured and accurate qualification plan, built upon four key areas including expected profile, quality requirements of an application, reliability data collected during product development, and degradation models. During the quality management process of CoolGaN, not only the device is tested but also its behavior in the application. The performance of CoolGaN goes beyond other GaN products in the market. It offers a predicted lifetime of more than 15 years, with failure rate less than 1FIT rate.

Designing wireless charging systems with GaN

Above it was explained why GaN technology provides many opportunities to increase overall efficiency of the system. But this does not come for free, the GaN technology has some attributes that need to be considered during system design. Design criteria to be taken into consideration:

Driving voltage accuracy

As specified in the data sheet, the absolute maximum rating for the V_{GS} of a MOSFET is typically ±20 V. This provides the designer some freedom to keep the voltage regulator of the driving stage relatively simple and cheap. With GaN this is not the case. The absolute maximum rating is limited to roughly 5 to 6 V. That is mainly due to the diode nature of the gate structure. If in operation the gate-source voltage exceeds this limit in worst cases, it could create severe damage to the device and at best reduction of lifetime. For this reason design of the voltage regulator used to create the driving voltage must be very careful, because a solution that works for silicon may not be suitable for GaN.

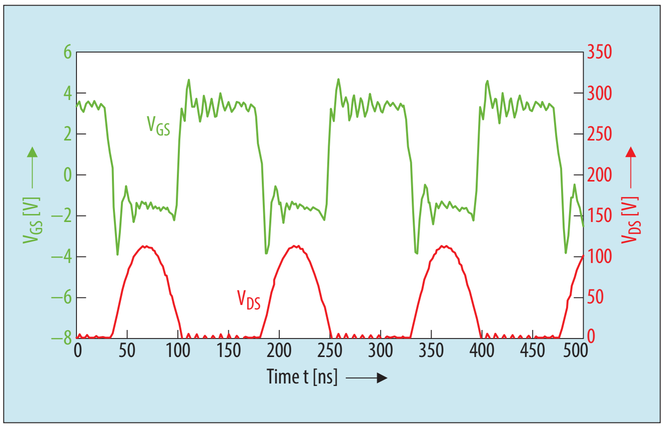

Fig 5. Waveforms of a single-ended E-mode amplifier with GaN HEMT.

Gate current

Behavior is different to silicon-based products, in which the gate is controlled through a gate oxide isolator. The gate connection for GaN devices takes the form of a Schottky barrier where the leakage current is consequently not in the range of nanoamperes but milliamperes. Care should be taken when selecting the gate drive voltage and drive network components.

Device area

As seen above, GaN technology provides greater power density resulting from the low $R_{DS(on)}$ x area figure. This results from the high conductivity of the electron gas (2DEG), which provides a very attractive feature to designers who want to increase the power density of their applications. But it also creates some challenges. The fact that the

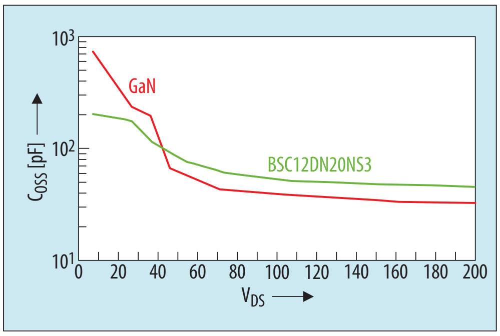

Fig. 6. Capacitance C_{OSS} as a function of drain-source voltage V_{DS} for silicon MOSFET BSC12DN20NS3 and GaN HEMT.

area is smaller implies that there will be less contact area to extract the power dissipated inside the device. During the layout phase, design of the power connections between the device(s) and PCB will be more demanding and the thermal resistance of the device could suffer. Since the most important thermal resistance is junction to ambient, which is mainly dictated by PCB characteristics, the smaller dimensions of the GaN device package should not create too much additional thermal resistance. In any case particular care should be taken during design of the PCB to minimize this thermal resistance, since the smaller area of the GaN might partially counteract the advantage of the technology. *ih*

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graduated in 2000 from Politecnico di Milano in system and signal engineering. He joined Infineon Technologies AG in 2006, where he has worked as an applications engineer for MOSFET technology definition in different application fields and voltage classes. Prior to joining Infineon, he was an applications engineers for drivers and controllers at STMicroelectronics.

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