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HOW GAN IS TRANSFORMING RF ENERGY AND COOKING APPLICATIONS

The RF energy market has evolved relatively slowly since magnetrons first came into widespread commercial use in microwave ovens in the early 1970s. Today, there exists a variety of use cases for RF energy, including industrial and consumer cooking, drying, lighting, medical, and automotive applications.

Recently, solid-state technology has appeared on the scene as a viable replacement and enhancement for magnetrons as the heating engine, delivering several key advantages: longer lifetime, enhanced reliability, precise power level and energy direction control, increased efficiency, and smaller dimensions.

Price and efficiency inhibiting growth

While the RF energy market is widely predicted to grow to as much as a billion dollars over the next five years, its expansion so far has been inhibited by solid-state technology limitations.

To reduce energy consumption requires high efficiency, less cooling or dissipated power heat sinking, which is an important consideration in all RF energy application designs. Ruggedness is critical for the harsh operating environments and unpredictable loads that the heating element is faced with during operation which, combined with the need for consistent power and long operating life, represents a huge disadvantage for existing magnetron technologies.

To date, the only solid state technology that has come close to the sector's tough cost targets has been silicon LDMOS. Driven by developments for basestations, LDMOS technology is well established with a competitive cost structure and volume supply chain. However, it falls short on efficiency (by more than 10%), ruggedness (due to lower breakdown voltage and lower operating temperature), and power density (which is only one-quarter to one-sixth of GaN).

GaN-on-SiC (gallium nitride on silicon carbide) can meet the necessary performance but has been unable to meet the necessary manufacturing scale and cost structure, and has traditionally been 5 to 10 times more expensive than legacy technologies – the physics of growing silicon carbide substrates is truly cost prohibitive even at large economies of scale.

However, as GaN transitions from traditional 4-inch compound semiconductor wafer fabs to 6-inch and 8-inch silicon fabs over the coming year, GaN-on-Si is starting to break through the cost threshold towards the ultimate goal set by the RF Energy Alliance of 5 cents per Watt, meaning that designers can finally move forward with mainstream deployment. For example, MACOM offers a 300W GaN-on-silicon device in plastic packaging that sells at around $15 and delivers over 70% efficiency. This level of price to performance has simply not been attainable until now.

RF energy in cooking applications

One of the largest potential RF energy markets today is found in RF cooking and heating applications. Well over 70 million microwave ovens are manufactured annually, spanning low-cost consumer grade to high-end professional and industrial ovens.

RF power transistors offer numerous performance advantages over traditional magnetrons, including better control of the cooking process through greater precision in setting the power level and RF energy direction inside the oven.

Today's microwave ovens lack effective control of the power level or the ability to direct the energy where required, which results in hot spots and over-cooking.

In the case of solid state devices, the frequency, amplitude, phase, pulse width and modulation can all be accurately controlled. With closed-loop control between the RF power amplifier and the RF synthesizer, a feedback loop enables the assessment of forward and reflected power levels, hence facilitating accurate and optimised control of the energy pattern.

This means that with three or four transistors and antennae, it is possible to direct the energy exactly to where it is required on the food, whilst the reflection and absorption of the radiation can be accurately measured. This feedback loop and the accurate control enabled by solid state transistors, enables an oven to accurately determine how well the food is cooked, and thus achieve reproducible results.

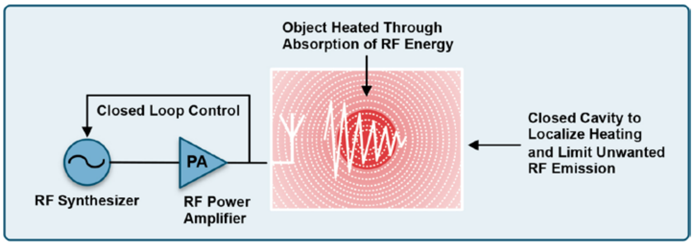

Figure 1 *Solid-state powered RF energy application*

Varying the phase between multiple antennae can enable the field distribution inside the oven to be intelligently controlled to achieve homogeneous cooking results. Furthermore, by modifying the frequency and phase to match the food in the oven, very high RF energy delivery efficiency can be attained – above 90% even for small loads.

It has been demonstrated how a steak can be cooked on the same plate as ice cream without it melting, showing the precision of the directed RF energy. In practice, one gets outstanding control over internal meat temperature, with a tight tolerance of just one degree Celsius. Therefore, food can be cooked automatically, and one simply specifies the steak "doneness" level, for example, medium rare; and the oven will measure the food's properties and calculate the required settings. Without having to manually enter the power levels, cooking is more predictable, and the interface more user-friendly.

As well as convenience, precise temperature control means that the cooked food is healthier and retains more of its nutrient content than is the case with traditional microwave ovens. The result is no more over-cooking or hotspots destroying nutrients and amino acid chains.

The solid state subsystem

For this kind of microwave oven application, a solid state RF generator subsystem could consist of the following:

- Small-signal generator, which may be co-located with a microcontroller
- High power amplifier connected to a heat sink
- Power supply

A block diagram for this system is shown below. The "RF Out" connection leads into an RF applicator, which may be a cavity or an otherwise confined environment. This contains the food absorbing the RF radiation and provides the required level of EMC shielding.

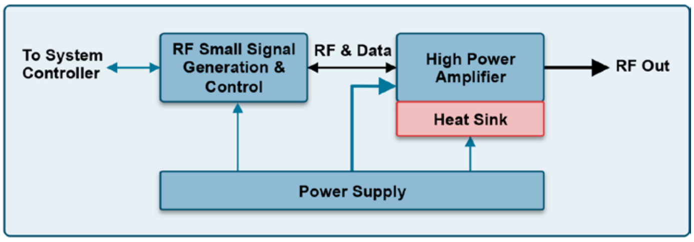

Figure 2 *Block diagram of a solid-state RF generator system*

Reliable and cost-effective

In cooking and heating applications, RF power transistors offer many times longer operating lifetime than magnetrons. The typical total lifetime of a magnetron could be around 1500 hours, compared to a million hours for GaN devices.

In a home microwave, where usage is low, a magnetron may last many years, so the long lifetime of GaN is not as crucial: however, this reliability advantage becomes vitally important in professional applications. For example, in catering, fast food establishments, restaurants or production bakeries; systems for mass-produced food may use entire arrays of magnetrons in their operations.

In a production environment where systems run 24 hours a day, 7 days a week, the magnetron ages quickly and performance declines. This means that today, technicians are frequently sent out to replace magnetrons – sometimes on a weekly basis. This is an expensive exercise, so switching to solid state GaN transistors has the potential to considerably cut service costs.

Although GaN still has a nominal price disadvantage, it does, however, provide some system cost savings compared to magnetron technologies. The power supply can be simpler, no flyback transformer is required, and there is no longer a need for a motor to rotate the platter. As GaN prices fall, these system advantages will increasingly offset the premium charged for the GaN component.

We expect initial traction primarily in the higher-end industrial and commercial cooking and defrosting market as the reliability and service cost saving factors become increasingly compelling. When one considers that a professional oven may cost $25,000, it becomes evident that a few extra dollars spent on components become more or less negligible. It is expected that this will be followed by traditional white-goods manufacturers implementing GaN in ovens for both the professional and consumer market.

Efficient and compact

Energy efficiency is an essential consideration with any piece of electrical equipment, and microwave ovens are no exception. GaN has a pivotal 10% efficiency advantage over LDMOS, and a much higher efficiency than a magnetron when cooking variable loads which is what an oven will see in reality. While silicon carbide has the potential to deliver competitive efficiency levels, it is never going to be sufficiently competitive on cost grounds.

Topic	SS RF Energy	Magnetron
Wall plug Efficiency (IEC standard test)	54% (LDMOS) > 64% (GaN)	17% .. 54%
RF delivery efficiency	> 90% always	uncontrolled 0..90%
Power level	Low to very high!	Fixed, high
Power supply	28V	4kV
RF Power control	> 20dB, fast	fixed
RF Energy control	> 40dB, fast	Fixed (slow duty cycle)
RF Frequency control	< 1MHz	n.a.
RF Phase control (multiple coherent sources)	< few degrees	n.a.
Reliability/ lifetime	> 10 years, hardly any performance degradation	5000hrs, some power droop!

Table 1. *Solid-state vs. magnetron, at 2.45 GHz*

The RF Energy Alliance, an industry body, is working towards a specification that defines the expected efficiency for cooking with solid state devices. It is recommending an overall system efficiency of 60% measured from the power outlet to the delivered power to food, and it is widely accepted that GaN is the only way of achieving such a target. China is currently considering adopting this as an energy standard, which is significant because China manufactures around 80% of the world's microwave ovens.

Looking beyond conventional microwave ovens, the compact size of these RF energy devices will open up a multitude of opportunities for new, innovative applications. For example, in Asia, there is a ubiquitous demand for rice cookers, and solid state devices could enable new table-top cookers in smaller form factors. Other innovative ideas include a mini-microwave for in-car use or tiny flask-sized cookers for hikers and tourists.

Related applications

As well as cooking, solid state devices will find their niche in industrial dryers, timber (lumber) drying equipment, manufacturing, food processing, agriculture, and waste management.

In the medical market, RF energy is used for tumour ablation and tissue storage applications. Medical ablation systems must be extremely compact, robust, and efficient; and solid-state technology meets these requirements precisely. Given its ability to fine tune power output, GaN will enable new medical applications that simply are not possible with existing magnetron technologies.

Fuel efficiency enhancement for automotive ignition systems is another emerging application. RF power is used to boost engine efficiency by facilitating a more complete combustion of the vapours in the engine chamber than is possible with standard spark plugs. This has the potential to enhance fuel efficiency by 10% and reduce nitrogen oxide and volatile organic compound emissions.

For all of these applications, the RF devices that drive them must achieve the right balance of performance, power efficiency, compact size, and reliability, while hitting a price point that is comparable to LDMOS, and which makes them affordable for mainstream use.

The GaN advantage

MACOM's GaN-on-Si technology is ideal for all these RF energy applications, offering performance advantages at a cost that is competitive with LDMOS. MACOM GaN-on-Si delivers efficiencies exceeding 70%, and high gains at 900 MHz and 2.45 GHz frequencies. These are the unlicensed frequency bands where industrial, scientific, and medical applications, such as RF energy, operate without interfering with licensed communications networks.

With the technology advantages of GaN-on-Si now becoming available at a competitive price level, it is undoubtedly a disruptive technology for RF power applications, particularly in industrial applications where higher reliability and performance justifies a greater initial investment. The first solid state microwave ovens are expected in professional applications within a year's time, with consumer devices following a year or two behind.

GaN-on-Si is inherently rugged and ideally suited for harsh environments with unpredictable load impedances, exhibiting no performance degradation over time. The MACOM GaN process is also scalable due to its silicon-based cost structure, and provides the capacity and reliability needed to trigger the explosive growth that is anticipated in this market.

About the Authors

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