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GaN Solid State Power Amplifiers for Microwave Power Transfer and Microwave Heating

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SUMMARY GaN solid state power amplifiers (SSPA) for wireless power transfer and microwave heating have been reviewed. For wireless power transfer, 9 W output power with 79% power added efficiency at 5.8 GHz has been achieved. For microwave heating, 450 W output power with 70% drain efficiency at 2.45 GHz has been achieved. Microwave power concentration and uniform microwave heating by phase control of multiple SSPAs are demonstrated.
key words: *solid state power amplifier, microwave power transfer, microwave heating, phase control, carbon neutral, harmonic termination*

1. Introduction

GaN devices have become the main player for the 5[th] generation mobile communication (5G) base transceiver stations [1] and infrastructure radar systems such as weather radar system [2]. In other words, GaN has already been successful in wireless telecommunication and wireless sensing fields. GaN devices are seeking for the 3[rd] filed to be employed in.

Recently, carbon neutral (CN), or reduction of carbon dioxide (CO_2) emission has become a critical global issue and many countries and enterprises are committed for CN. There are two main issues for CN. The first one is conversion from fossil energies to reproducible natural energies. Among of reproducible natural energies, solar energy is dominant so far and will continue to be the most important part. However, solar power is susceptible to weather conditions and unstable. To address this problem, space solar power systems (SSPS) are proposed [3]. In Fig. 1, an image of SSPS is shown schematically. By launching a huge satellite equipped with many solar cell panels and a microwave transmitter, solar energy is converted to microwave energy and transmitted from space to the earth. In SSPS, C-band microwave (5.8 GHz) is used to transmit energy from SSPS to the earth, where microwave energy is rectified and converted to DC energy again. The efficiency of the microwave transmitter is the most important factor which determines overall efficiency of SSPS system, which is the ratio of obtained DC output power on the earth with respect to solar energy received at solar cells. GaN amplifiers is regarded suitable for the transmitting amplifier since its efficiency has become very high.

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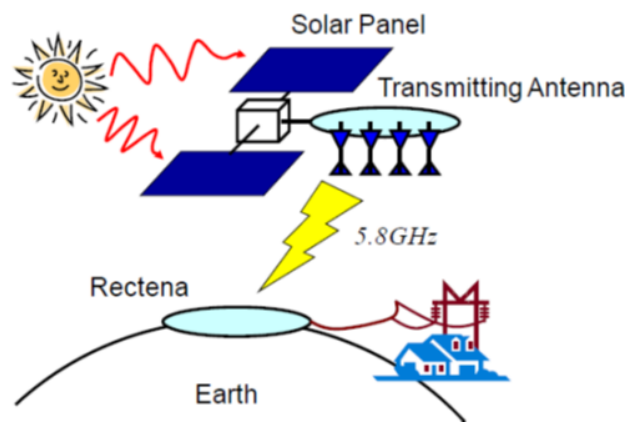

Fig. 1 Space solar power systems

The second point for CN is to reduce energy consumption. Roughly 1/3 of energy is consumed in the industry and heating process is dominant for the energy consumption there. So far, external heating processes such as chamber heating or steam heating have been employed. These kind of external heating methods consumes fossil energies and exhaust much CO_2. Moreover, external heating methods are very inefficient since external heating consumes energy to heat its chamber rather than heat target materials. To address this problem, microwave heating is attracting attentions [4]. Microwave can heat materials directly. Therefore, its heating efficiency is very high. In other word, microwave ovens are adopted to industrial material heat processes. For microwave heating, ISM (Industry, Science and Medical) bands have been used, such as 900 MHz, 2.45 GHz and 5.8 GHz. Among them, 2.45 GHz is the most important frequency, especially in Japan, since 900 MHz is close to mobile phone band and care is needed to suppress interference. 5.8 GHz is not major for ISM band so far. Components at 5.8 GHz are rather costly compared with 2.45 GHz.

For microwave heating, vacuum tube devices such as magnetrons have been used since microwave heating requires such high power as over 1 kW. However, lifetime of magnetrons is generally short (roughly 1~3 year) and they should be replaced once every year. Recently, semiconductor-based microwave power source, namely solid-state power amplifiers (SSPAs), for microwave heating has been developed vigorously. In Table 1, comparison of magnetron, LDMOS (Laterally Diffused Metal Oxide Semiconductor) SSPA [5]

Table 1 Comparison of Magnetron, LDMOS and GaN

	Magnetron	LDMOS	GaN
Output Power of Single device	~6kW	~250W	~420W (expected)
Phase coherence	No	Yes	Yes
Efficiency	~70%	~60%	~65% (expected)
Cost	~$1k/kW~	~$3k/kW	TBD
Lifetime	1~3 year	~10 year	~10 year

and GaN SSPA is shown. At this moment, there is no commercially available GaN SSPA for microwave heating. Therefore, GaN SSPA performance is estimated from performance of GaN high power amplifiers. From viewpoint of output power, magnetrons are superior to SSPAs. However, output power of SSPAs can be combined to get higher power, even up to some kW, since they are phase coherent. From viewpoint of efficiency, magnetron is slightly superior to SSPAs, but SSPA efficiency is getting better and better. Also, cost of SSPAs is decreasing drastically. It will be comparable to magnetron in near future. Considering material properties, GaN is more suitable than LDMOS. GaN SSPA will play important role for microwave heating to realize CN.

In this paper, 5.8 GHz GaN amplifier for wireless power transfer and 2.45 GHz GaN amplifier for microwave heating are reviewed. As a showcase of SSPA's merits, experimental results of microwave power concentration and uniform heating are shown. Finally, future prospect of SSPAs for microwave power transfer and microwave heating are discussed.

2. 5.8 GHz GaN Amplifier for Wireless Power Transfer

In Fig. 2, the circuit schematic of the 5.8 GHz GaN amplifier [6] is shown. It consists of a GaN HEMT chip, quarter wavelength impedance transformers and open circuited stubs for harmonic terminations. Input and output impedances of the amplifier are matched to 50 ohm. Gate length of the GaN HEMT is chosen to 0.25 micron. This short gate length GaN HEMT is usually used for Ku-band (12.4 GHz ~ 18 GHz). To obtain high efficiency, harmonic tuning effect should be maximized since efficiency of the amplifier is finally determined by class of operation. To realize ideal operation class, short gate length GaN transistor is used. For input side, only the 2nd harmonic is controlled since effect of the 3rd harmonic at input side is negligible. Meanwhile, the 2nd and the 3rd harmonics are carefully controlled since both affect the efficiency of the amplifier. Positions of the harmonic reflection stubs are determined from measurement results of harmonic load-pull.

Photograph of the 5.8 GHz internally matched GaN HEMT is shown in Fig. 3. Input matching circuit is made on a high dielectric substrate ($\varepsilon_r = 38$) while output matching circuit is made on an alumina substrate. Effective circuit size is 8 mm × 8 mm and all circuit components are packed in a hermetically sealed metal package. The amplifier exhibited 70% power added efficiency (PAE) together with 7.1 W output power with 30 V drain voltage.

To improve the efficiency, the easiest way is to reduce the gate length since it enhances the harmonic tuning effects. In Fig. 4, output power, gain, PAE vs input power of 0.15mi-

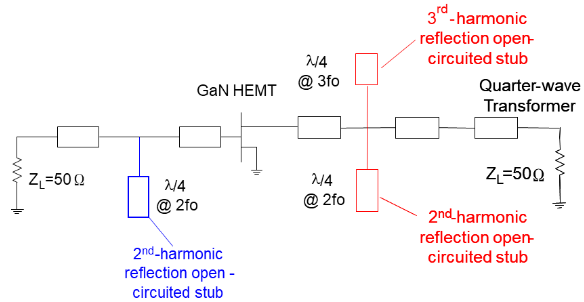

Fig. 2 Circuit schematic of the 5.8 GHz GaN amplifier [6]

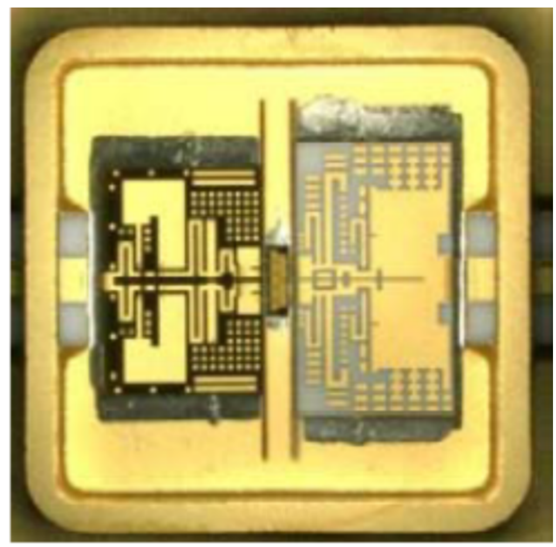

Fig. 3 Photograph of the 5.8 GHz internally matched GaN HEMT high efficiency amplifier [6]

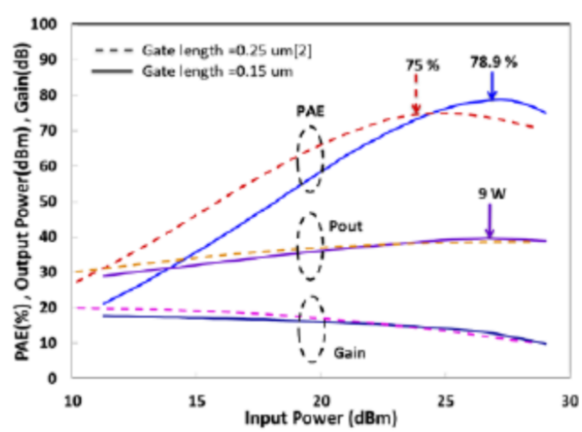

Fig. 4 Output power, Gain, PAE vs input power of 0.15micron GaN HEMT amplifier [7]

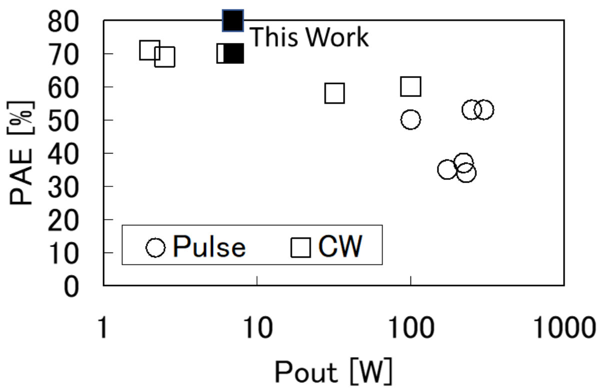

Fig. 5 State-of-the-art of C-band GaN amplifiers

cron GaN HEMT amplifier are shown. The circuit is almost same as shown in Fig. 2 and Fig. 3 except of slight tuning. 78.9% PAE was obtained together with 9 W output power. This is the record high efficiency for 5.8 GHz GaN amplifier for the time being. Comparison against other published works [8]–[14] are shown in Fig. 5.

3. 2.45 GHz GaN Amplifier for Microwave Heating

For microwave heating, both high output power and high efficiency are required. A 400 W class CW operation GaN high power amplifier is designed and manufactured [15]. In Fig. 6, photo of the developed 2.45 GHz high power and high efficiency GaN power amplifier is shown. It consists of two GaN HEMT chips, each has total gate width of 38.4 mm. Circuit topology is same as Fig. 2 except that only the 2nd harmonic is terminated (the 3rd harmonic is omitted) since the 3rd harmonic tuning was very difficult for this kind of large gate periphery chips and tuning the 3rd harmonic may cause a significant increase of circuit loss at the fundamental frequency. The 2nd harmonic at input side was terminated with on-chip pre-match circuit.

In Fig. 7, measured output power, drain efficiency, gain vs input power are shown. The measurement was done with 50 V drain voltage. At peak, 70% drain efficiency was successfully obtained. This number is close to that of commercially available magnetrons for microwave ovens. Considering circuit losses of SSPAs after final stage amplifiers, which is typically 0.3 dB, total SSPA output power would be 420 W and efficiency would be 65%.

To reduce cost of GaN amplifiers, GaN-on-Si amplifier was also developed [16]. In Fig. 8, measured output power, drain efficiency (DE), PAE, gain vs input power of GaN-on-Si amplifier are shown. The measurement was done with 30 V drain voltage at 2.15 GHz. 170 W output power was successfully obtained with peak PAE of 60%. These results are compared with other published works [17]–[22] in Fig. 9.

4. Phase Control Demonstration of GaN SSPA

As is mentioned in the introduction, one of advantages of SSPA against magnetron is that SSPA is phase coherent while

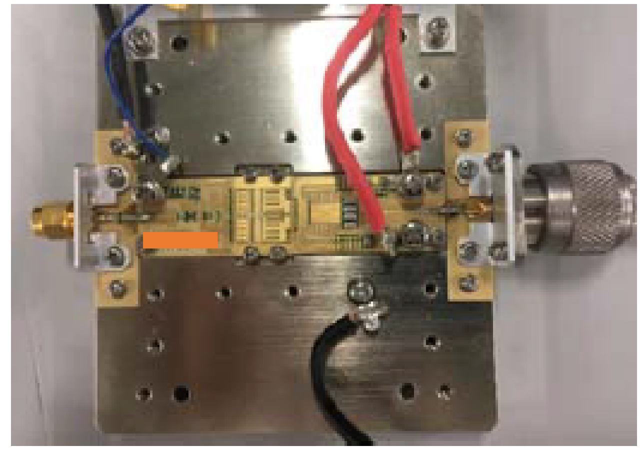

Fig. 6 Photo of the developed 2.45 GHz high power and high efficiency GaN power amplifier [15]

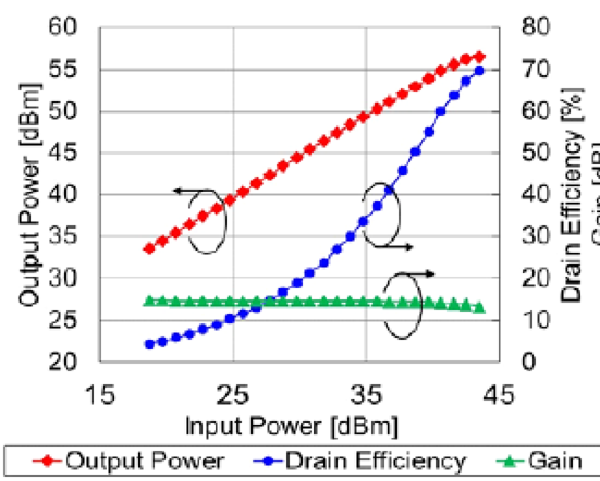

Fig. 7 Output power, drain efficiency, Gain vs input power [15]

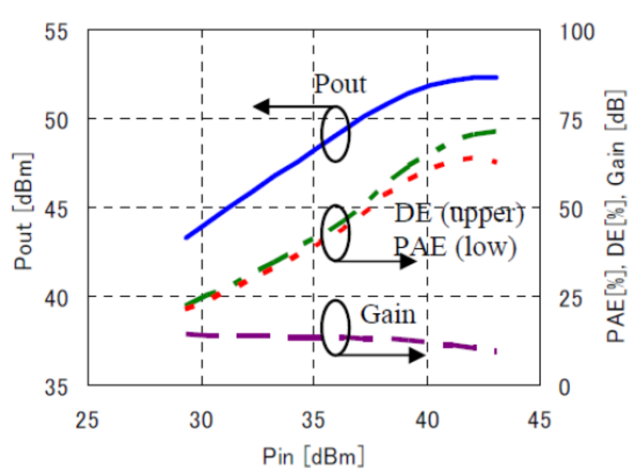

Fig. 8 Output power, DE, PAE, Gain vs input power of GaN-on-Si amplifier [16]

magnetron is NOT phase coherent, except for the case of injection locked magnetrons [23].

To demonstrate the merit of phase coherence, beam

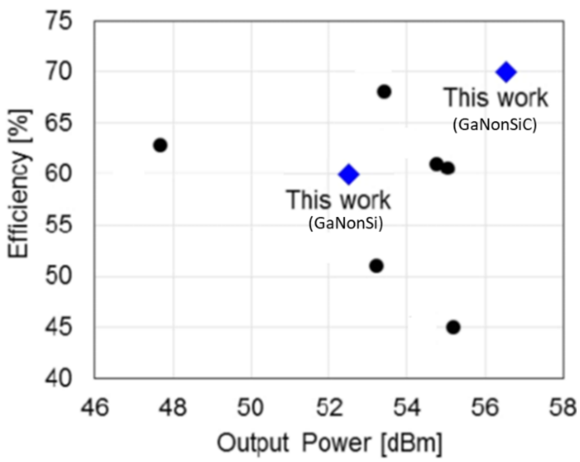

Fig. 9 State-of-the-art of 2.45 GHz high efficiency GaN amplifiers

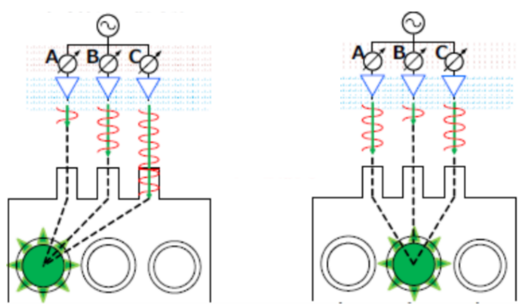

Fig. 10 Principal of phase-controlled microwave power steering [24]

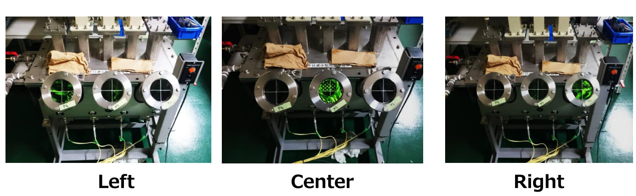

Fig. 11 Experimental result of phase-controlled microwave power concentration [24]

forming and steering in a microwave cavity was demonstrated [24]. Principal of phase-controlled microwave power steering is shown in Fig. 10. There are 3 microwave input ports to the cavity. At each port, SSPA operating in 2.45 GHz is attached together with phase shifters (A, B, C). Microwave signal from the source is divided into 3 ports, but they keep coherence. By setting phase difference between these input ports, microwave energy fed into the cavity is controlled as shown in Fig. 10. To visualize microwave power, array of rectennas connected with LEDs are placed in the cavity. When a rectenna unit was irradiated by microwave, LED connected to the rectenna turns on green. Figure 11 shows the experimental result of phase-controlled microwave power concentration. By setting phase shifters A, B, C, microwave power is concentrated at the left-hand side, the center, or the right-hand side. This result means that phase-controlled microwave heating cavity can heat any part selectively.

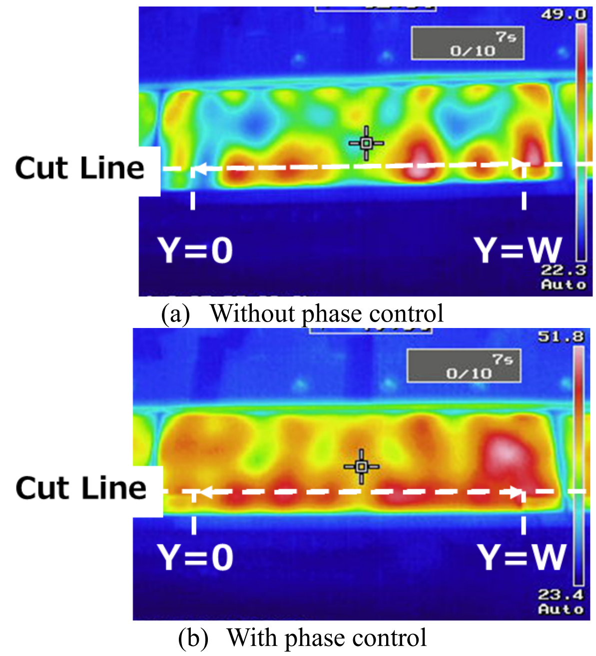

Fig. 12 Results of uniformed microwave heating [25]

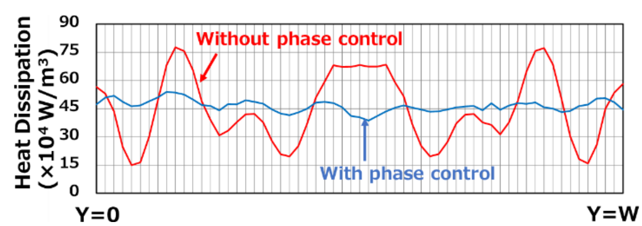

Fig. 13 Heat dissipation profiles [25]

For actual use case in the industry, uniform heating will be more important than selective heating. By setting phase difference adequately, uniform heating is also achieved [25]. In Fig. 12, the results of uniform microwave heating are shown. Operating frequency is 2.45 GHz, heating area width W is 60 cm, and other details of the experimental setup is described in [25]. In the figures, red part is "hot" while blue part is "cold". As can be seen in the figures, without phase control, heat dissipation is non-uniform while it is rather uniform with phase control. Figure 13 shows the heat dissipation profiles along with the cut lines shown in Fig. 12. For the case of without phase control, heat dissipation varies roughly 5 times (from 15 to 75) while fluctuation for with phase control case is as small as 16% (from 37 to 52).

As shown above, phase controlled SSPAs can realize either concentration heating or uniform heating by just setting phase differences. This capability is desirable for microwave material heating processes.

5. Future Prospect of SSPAs for Wireless Power Transfer and Microwave Heating

As is mentioned so far, GaN SSPAs are promising for wireless power transfer and microwave heating applications. However, there still are some challenges for SSPAs to be widely deployed in industry.

Total power should be raised to some kW at least. Some 100 kW to MW will be required in future. To achieve such high power, special power combining technique is necessary. Also, power density of semiconductor devices should be higher than now. Table 2 summarizes comparison of SSPA devices in future. GaN-on-Diamond [26], [27] and Diamond transistor [28], [29] are considered to have several times higher power density compared with incumbent GaN-on-SiC devices. By using these devices, SSPA output power will be multiplied.

Thermal conductivity of the substrate will be crucial as power density of the device increases. GaN-on-Diamond and Diamond devices enjoy very high thermal conductivity of diamond substrate and hence are advantageous for kW operation.

One of the most important challenges for SSPA will be efficiency. Currently estimated 65% efficiency is NOT enough for GaN SSPA to be used widely. At least 70% efficiency is essential. GaN-on-GaN [30], [31] is considered to have better efficiency than GaN-on-SiC. It is considered that crystalline defects which arise from hetero-epitaxy between SiC substrate and GaN epi-layer cause efficiency degradation. GaN-on-GaN, which is totally home epitaxial, will be defects free and from +5 to +10 percentage point efficiency improvement can be expected.

Another most important challenge is cost. From viewpoint of cost, GaN-on-Si device seems promising since cost of substrate is substantial for microwave power devices. However, care must be taken for the fact that GaN-on-Si device performance decreases as ambient temperature (Tamb) increases [32]. Figure 14 shows measured and simulated large-signal characteristics of GaN-on-Si transistor at room temperature (Tamb = 300 K) and elevated temperature (Tamb = 394 K). It is obvious that both output power and PAE drastically decrease as Tamb increases. By large-signal transistor model analysis, it was found that these degradations are due to increase of substrate leakage current at elevated temperature. Therefore, improvement of substrate current leakage at elevated temperature is a must for GaN-on-Si to be employed. If cost of SSPAs is decreased as low as magnetrons, SSPA will be rapidly employed in microwave heating systems.

Operation frequency is also to be considered. Currently, 900 MHz, 2.45 GHz and 5.8 GHz are popular for wireless power transfer and microwave heating. However, higher frequency, such as 24 GHz, leads to smaller size of antennas. Especially for wireless power transfer, planar array antenna is usually used for beam steering. The higher the frequency, the smaller antenna size can be. 24 GHz or even higher frequency SSPAs are expected to emerge in future.

Table 2 Comparison of SSPA devices in future

	GaN-on-Dia	GaN-on-GaN	GaN-on-Si	Diamond	Ga_2O_3
Power Density	Very Good	Good	Poor	Very Good	Very Good
Thermal Conductivity	Very Good	Medium	Poor	Very Good	Poor
Cost	High	Medium	Very Low	Very High	Low?
Efficiency	Good	Very Good	Medium	Good?	Poor??
High Frequency operation	Good	Very Good	Good	Medium	Very Poor

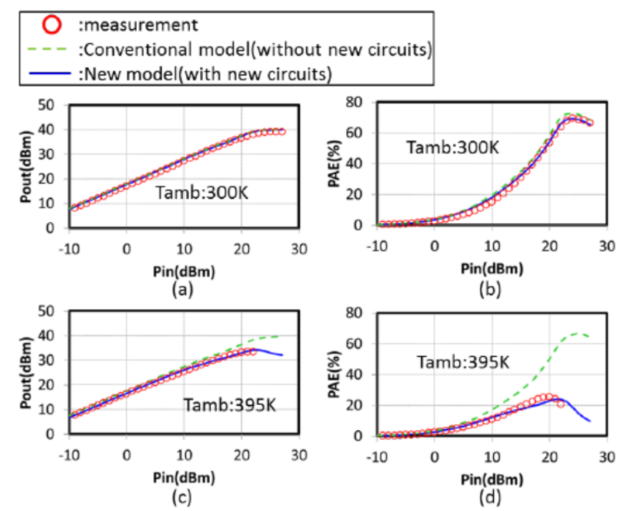

Fig. 14 Measured and simulated Large-signal characteristics of the GaN-on-Si transistor at room temperature (Tamb = 300 K) and elevated temperature (Tamb = 394 K) [32]

6. Conclusion

GaN solid state power amplifiers for wireless power transfer and microwave heating have been reviewed from some published papers. By using harmonic termination, efficiencies of GaN high power amplifiers are raised to 79% for 9 W for 5.8 GHz amplifier and 70% 450 W for 2.45 GHz amplifier. These numbers are well enough for GaN SSPAs to be employed for a certain application. For wide-spread application of SSPAs, more improved performance and lower cost are desired. New devices such as GaN-on-Diamond, GaN-on-GaN, or GaN-on-Si, Diamond transistor could be candidates of future SSPAs.

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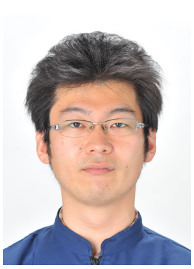

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