AlGaN/GaN Heterostructure Field Effect Transistor Free-Space Combining Oscillator Arrays: An Approach for Solar Power Conversion to High RF Power For Wireless Transmission to Earth

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September, 2002

Outline

- Introduction
- Wireless Power Transmission Considerations and System Definition
- Oscillator Approaches
- AlGaN/GaN HFETs for RF Signal Sources
- Conclusions

Motivation

• Predictions of the power needed in 50 years or so imply commercial power levels usages 3 to 5 times greater than today's. Meanwhile, power generation cost per kWh need be about 10 times less

• Earth-based solar cell power generation at the predicted level by 2050 implies an unrealistically large earth surface area (about 1/5 of the entire United States).

• The proposed Wireless Power Transmission (WPT) by means of spatial power-combining oscillator arrays that employ high power widebandgap semiconductor devices offers an alternative solution

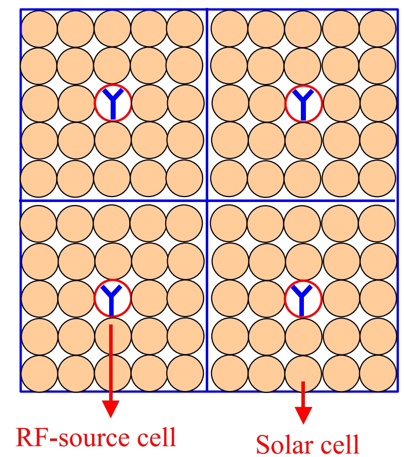
Program Objectives

The proposed studies address basic scientific questions in:

- semiconductor technology and in particular III-V nitride and SiC widebandgap devices
- RF sources
- integrated arrays
- spatial power combining
- RF matching networks
- These studies will be performed with the long-term objective of satisfying projected needs of 2kW per person in 2050 translating to 20 tera Watts.

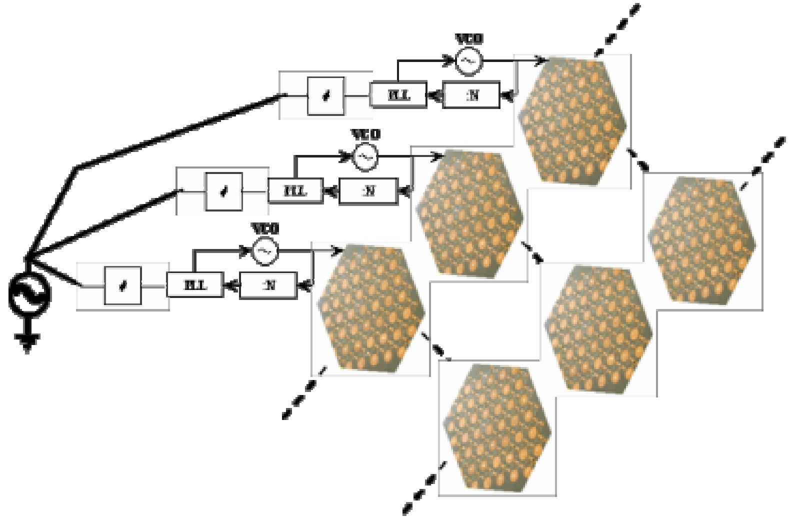
Proposed Scheme

Basic solar cell/RF source array



- Solar cell arrays made of low cost Silicon wafers are combined with RF sources which are implemented in the same array.
- Other possibilities include the use of SiC photovoltaic elements, which have advantages in terms of radiation resistance, thermal conductivity and high quantum efficiency.
- Consider 30% DC to RF conversion efficiency, with the a single RF source cell per 5x5 array of solar cells → RF power of 1.8W → as many as 300 GaAs MESFET devices are required for the proposed application.
- GaN HFETs with a tenfold power advantage compared with GaAs offer tremendous savings in terms of RF source cells, leading to significant cost reduction and reliability improvement.

The sub-harmonically injection locked large array approach

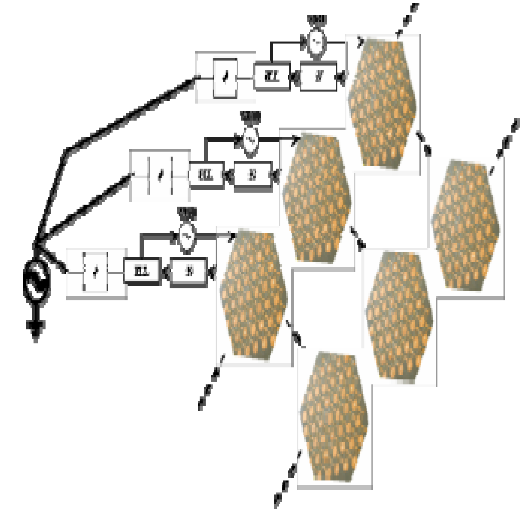


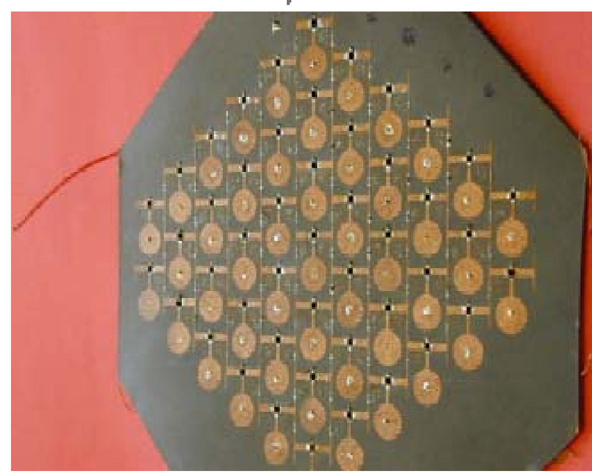
- A large active array is constructed by phase locking many sub-arrays which are injection locked to a voltage-controlled oscillator (VCO) to improve its stability.
- The VCOs are phase locked to a sub-harmonic master oscillator distributed across the large array either via coax cable or optical fiber.
- Phase shifters: correction of unequal path delays and tuning of radiated beam.

➔ study fundamental issues associated with injection locking in large antenna array: phase jitter across the whole array; existence of multimodes and parasitic oscillations; phase locking bandwidth and its near the carrier phase noise, which will impact the microwave beam shape and integrity.

Why Finite Array Analysis?

- Goal is:
  - to design a highly stable, efficient and multimode-free oscillator array that is tolerant to multiple device failures.
  - study fundamental issues associated with injection locking of the large antenna array (phase jitter across arrays, multimodes etc.)
- Large finite arrays must therefore be analyzed as a single unit rather than in periodic form.
  - Since the oscillator circuit and the radiating element can strongly interact, edge effects of the array are likely to affect oscillator stability.
  - Oscillator circuit and antenna must be modeled as a single unit leading to excessive computational needs involving millions of unknowns.



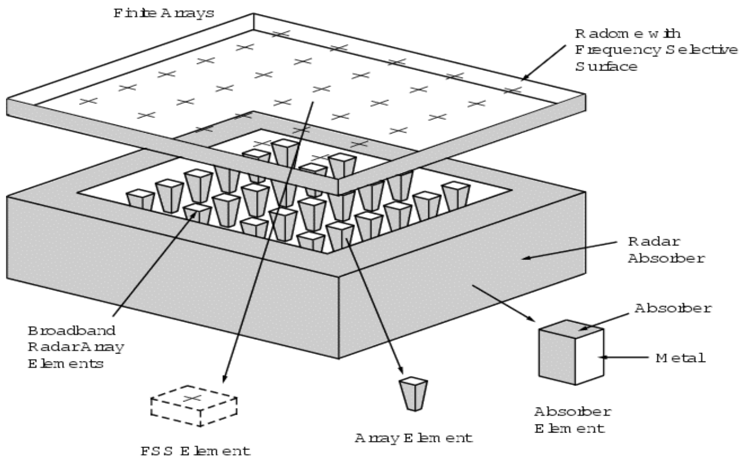


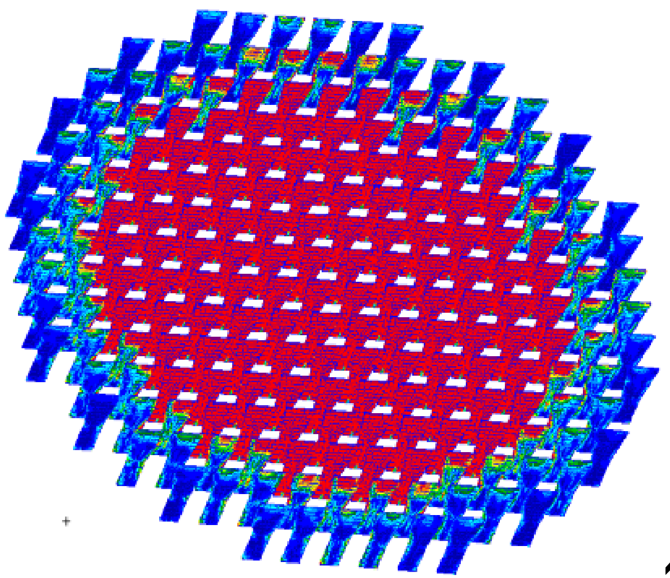
injection locked oscillator array

Finite Array Analysis Method

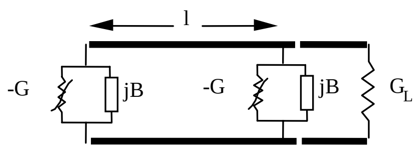
- New array decomposition method [*] will be used for large array array analysis without approximations
- Each element accurately modeled but repeated for storage savings
- For equally spaced elements FFTs allow for significantly lower CPU and memory requirements
- Preconditioners allow for very fast convergence
- 100x100 arrays involving 6.5 million unknowns have already been analyzed in less than 6 hrs of solve time and only 1.1GB storage

[*] R.Kindt, K.Sertel and J. Volakis, IEEE AP-T, 2002.

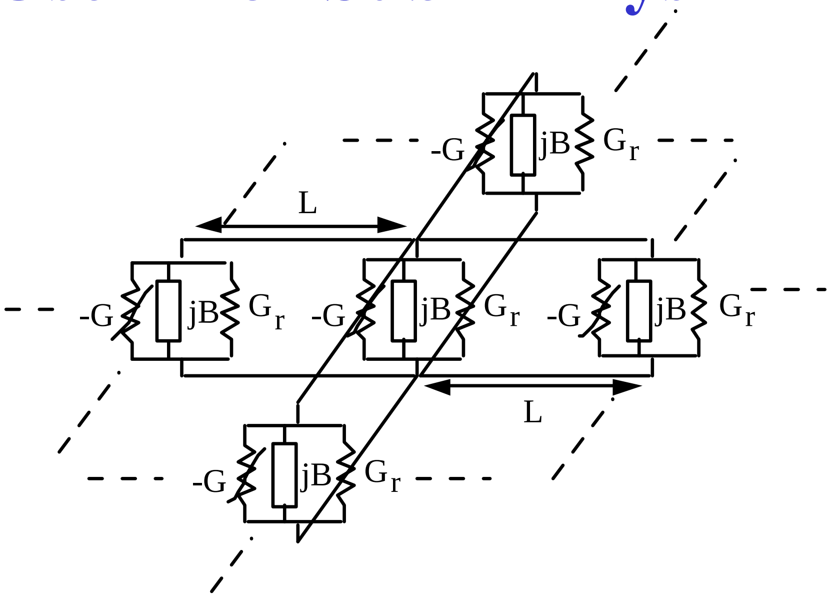




Extended Resonance Oscillator Sub Arrays



A two device network based combiner

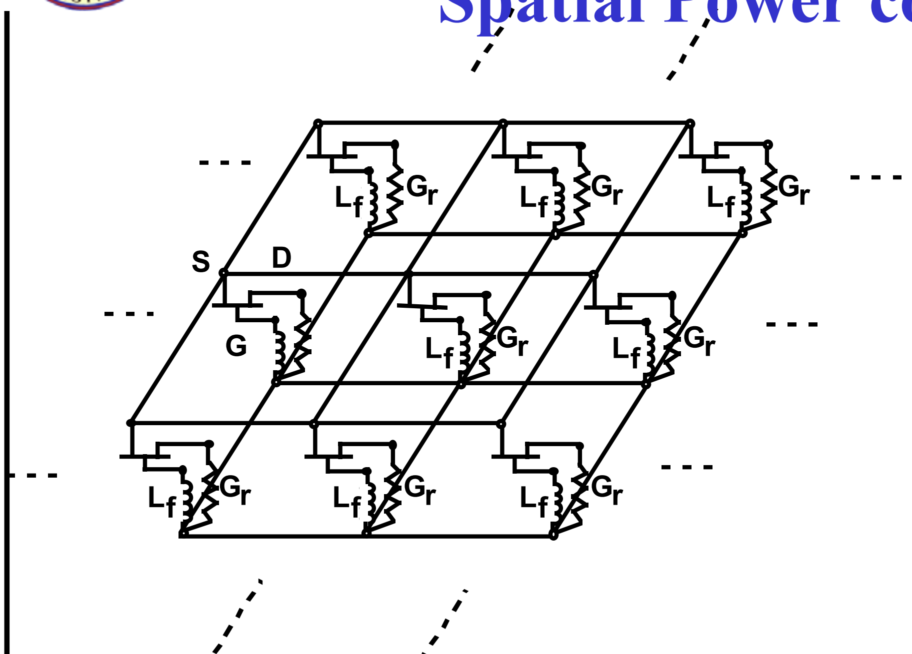


The equivalent circuit for a spatial combiner

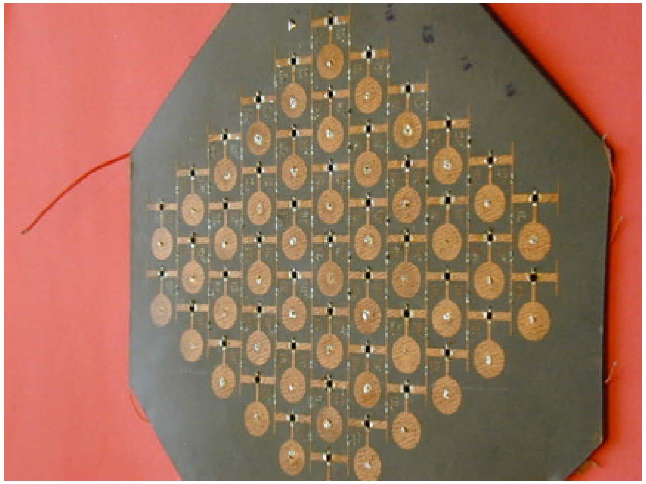
- By canceling the susceptances of two devices with each other, one can form a resonant circuit which determines the oscillation frequency.

The linear resonant circuit can be extended into two dimensions. The load is distributed at each device port and is replaced by printed antennas.

Circuit Implementation of the Extended Resonance Spatial Power combining Oscillator



Equivalent circuit for an extended resonance quasi-optical oscillator



Circuit implementation of a 36 device injection locked oscillator array

Two terminal devices can be replaced with transistors in an extended resonant Circuit.

- **Circuit implementation of the extended resonant spatial**
- **Power combining oscillator. This circuit can achieve single mode stable operation at the design frequency.**
- **Printed circular patch antennas provide a low profile and compact radiating array.**

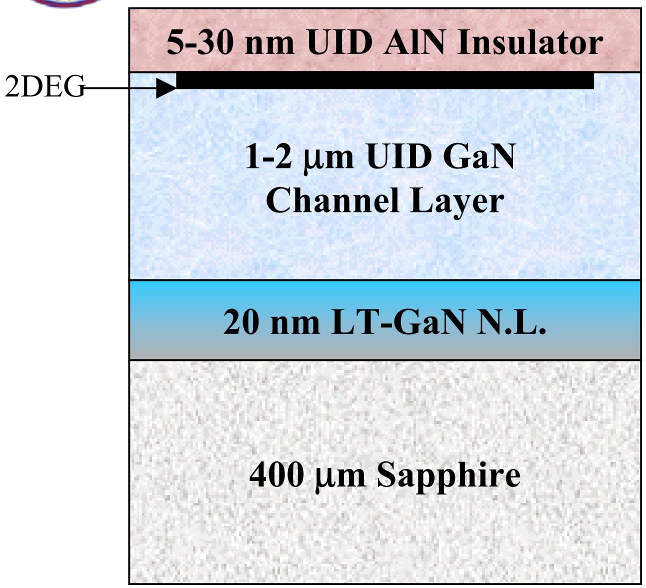
Power Advantages of III-V Nitrides

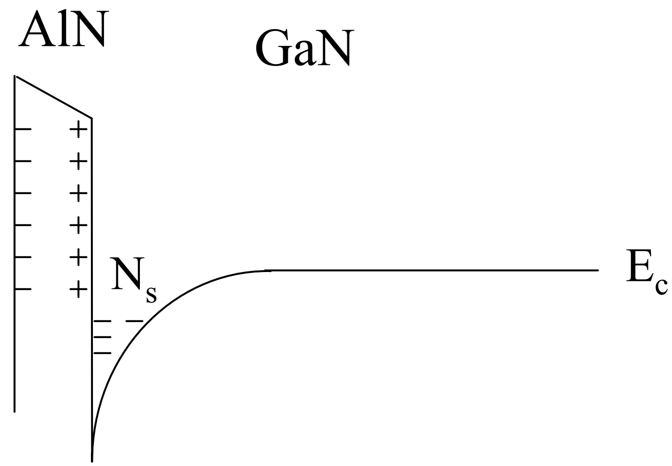
- Wide-bandgap (*3.4eV*) Gallium-Nitride based semiconductors were used for realization of blue diode lasers and demonstration of FETs with record power density *>10W/mm* at X-band
  ⇒ GaN-based FETs can be used for high-power control applications
- Studies of electron transport in GaN suggest *v-F* characteristics with a region of negative differential mobility, high threshold and critical fields, and reduced energy-relaxation times
  ⇒ GaN NDR diodes can be used for high-power mm-wave generation as an alternative to Three-Terminal Devices

Material Parameters and MSG Figure-of-Merit

Material	F_{TH}, [KV/cm]	F_B [MV/cm]	v_{SAT}, [cm/sec]	v_{PEAK}, [cm/sec]	$Pf^2Z=F_B^2 v_{PEAK}^2/4$ [normalized to GaAs]
GaAs	3.5	0.4	0.6×10^7	1.5×10^7	1
InP	10.5	0.5	1.2×10^7	3×10^7	36
GaN	~80-150	2	2×10^7	2.9×10^7	2000-7000

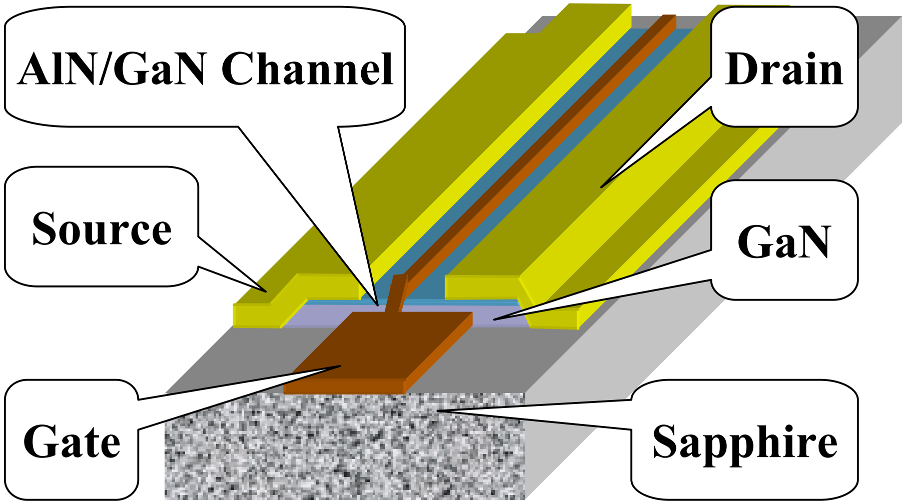
AlN/GaN MIS Heterostructures

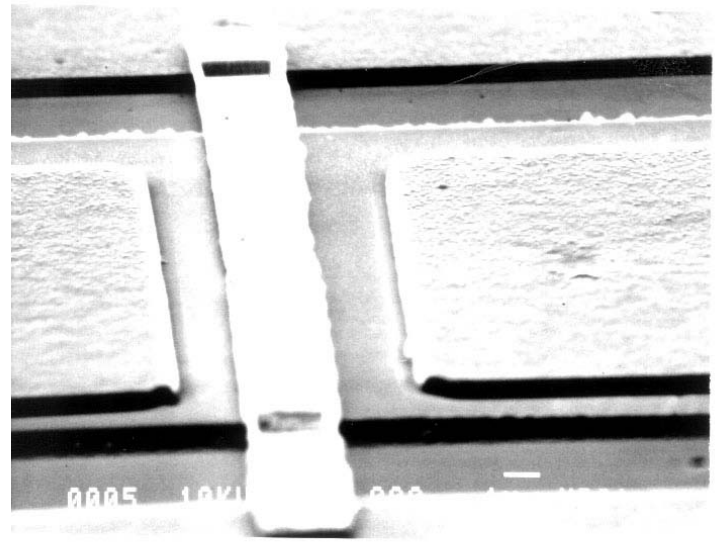




- Use of lattice-mismatched (2.48%) AlN/GaN system
  - ⇒ Induced Piezoelectric charge due to tensile strain
  - ⇒ Polarization charge due to material
  - ⇒ Ga-face MOVPE material → 2DEG at lower AlN/GaN interface
    - High density 2DEG due to AlN
- AlN insulator allows for realization of Metal-Insulator-Semiconductor (MIS) FET Devices => Potential candidate for Heterostructure Field Effect Transistor Free-Space Combining Oscillator Arrays

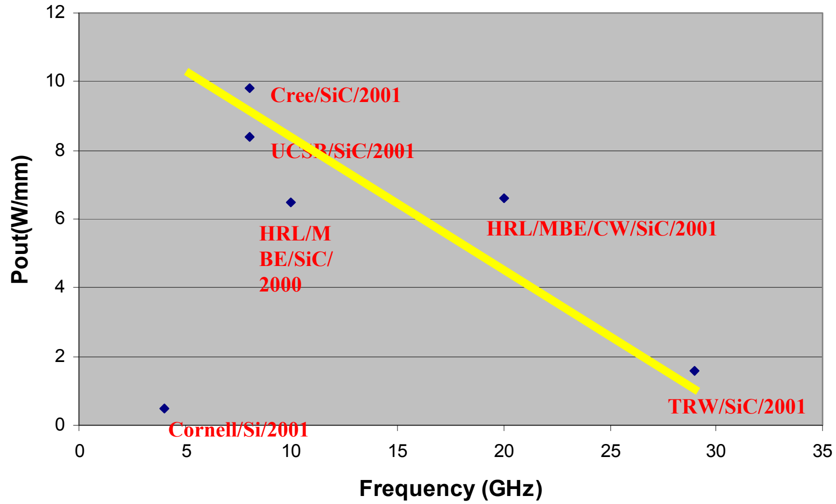
Fabrication of AlN/GaN MISFETs

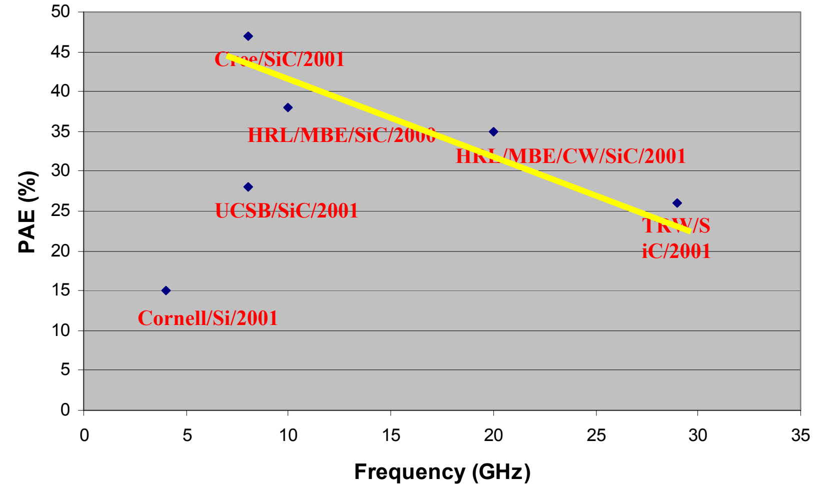




- MISFET layers had *0.6μm* GaN channel and thin AlN barrier
- AlN/GaN layers grown by MOCVD (TMGa, TMAl, and NH_3)
- AlN thickness was varied to maximize electron mobility
- CCl_2F_2-based RIE was used to isolate device mesas
- *Ti/Al/Ti/Pt* was used for ohmics and *Pt/Ti/Au* was used for gates

Power Characteristics of AlGaN/GaN HEMTs





- **Maximum power density of >10W/mm and PAE of ~60% have been reported at X-band**
- **Output Power of 14.5W (7.2W/mm) with 2mm gate width at 8.2GHz => excellent power level capability of GaN Heterostructure Field Effect Transistor Free-Space Combining Oscillator Arrays**

Frequency (GHz)	Gate width (mm)	V_{DS} (V)	Condition	P_{out} (W)	Output Power Density (W/mm)	PAE (%)	Institute	Substrate
8	0.15	24	CW	0.98	6.5	**60**	Cree	SiC
10	0.15	45	CW	**1.61**	**10.7**	**40**	Cornell	SiC
8	1	30	5μS, 5%	**8.5**	**8.5**	**38**	Cree	SiC Flip chip

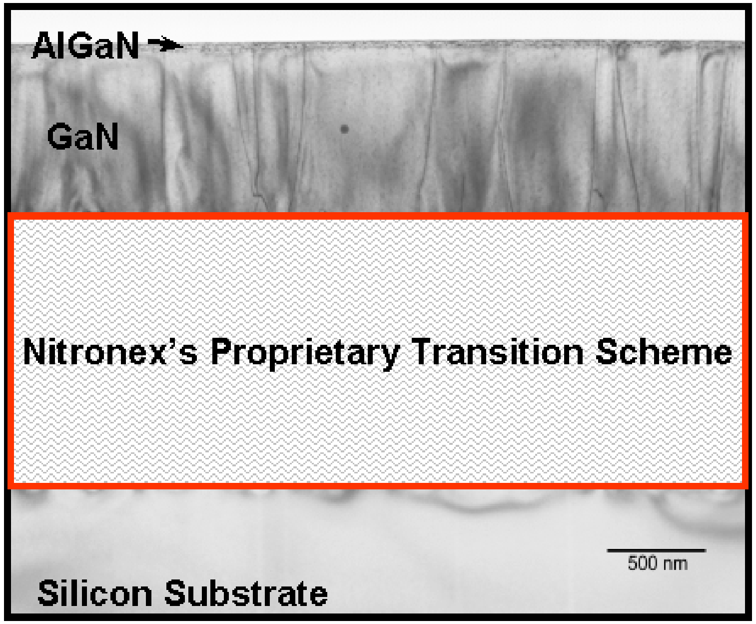
Hvbrid AlGaN/GaN HEMT- Based Amplifiers

Author	Publication year	Gain (dB)	Noise Figure (dB)	Output Power (W)	Band Width (GHz)	PAE (%)	Frequency of measurement (GHz)	Class of amplifier
Palmour et al. (Cree)	2001	8	-	38 CW	-	29	10	AB
Palmour et al. (Cree)	2001 2-stage	12.8	-	24.2 Pulsed	Wide	22.2	16	AB
Welch et al. (Wright-patterson AFB)	2001	8.5	3				4	A
Sheppard et al. (Cree)	2000	10.8	-	40.7 Pulsed		20	10	A
Wu et al. (NCKU Taiwan)	1999	11.5		3.1	3-9	20	8	
Sheppard et al. (Cree)	1999	7.1		9.1 CW		29.6	7.4	

Further evidence of power capability of GaN Heterostructure Field Effect Transistors for Free-Space Combining Oscillator Arrays

GaN on Si Device Considerations

- SIGANTIC® growth technique for GaN on Si developed by Team Member Nitronex offers the possibility of easier processing and compatibility with large wafer sizes and lower production costs
- AFM surface roughness
  - RMS < 25 Å for 10 mm x 10 mm area
  - RMS < 10 Å for 5 mm x 5 mm area
- XRC FWHM = 750 sec for GaN (0002)
- Defect Density = $2x10^9/cm^2$
- Hall Mobility = > ~ 1600 cm^2/Vs
- Sheet Carrier Conc = $1.2'13cm^{-2}$
- Crack Level < 0.0001 $\mu m/\mu m^2$



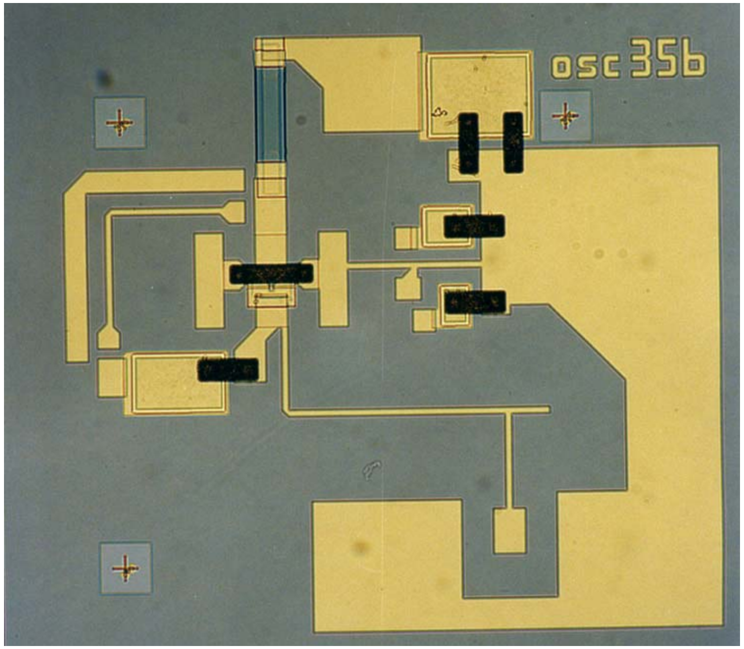
- **Results indicate great promise for device applications for GaN on Si HFET technology**

→ **Compatibility with proposed array approach for wireless power transmission**

MMIC GaN HFET Oscillators

- Oscillators using three-terminal devices AlGaN/GaN HFET's

  → establishment of negative resistance conditions through feedback circuits implemented on the signal generating subarrays
- MMIC oscillators with three-terminal device have very high DC-to-RF conversion efficiency. Example: >36% at Ku-band demonstrated at UofM (see photo) and a state of the art 61% efficiency has been reported at L-band using again HEMTs
- Large power capability of AlGaN/GaN HFETs is compatible with the very high voltage produced by solar cells → operation without a need for significant reduction.



- **Devices will be optimized with a view to small knee voltage and high gain → short gate lengths, high doping and thin channels**
- **Other studies: HFET nonlinearities, noise, injection locking**

Conclusions

- A novel approach for wireless power transmission has been discussed
- Collaboration is envisaged with with NASA Glenn and Nitronex.
- The proposed approach employs widebandgap semiconductor devices for MMIC injection-locked oscillator circuits, sub-harmonically injection locked large array and finite array analysis
- GaN on Si and SiC technology are promising for the proposed approach due to their compatibility with Si and SiC-based sollar cell power generation
- The advantages of the propposed injection-locked self-oscillating active antenna system are multifold:
  - Not prone to single point failure, even many active elements fail
  - Lightweight since it utilizes solid-state devices.
  - No complicated microwave power distributed network is needed
  - No active cooling; heat is distributed across the array and dissipated through radiation.

Conclusions (Cont'd)

- Low cost: Individual active antenna elements can locally be connected to arrays of solar cells; it is not therefore necessary to distribute large amounts of DC power across the large array; consequently the DC power distribution does need to be capable of delivering large power levels,
- Wide bandgap solid-state devices such as GaN HFETS allow for efficient high power oscillator arrays. GaN devices are well suited for operation in outer space where high-energy particles and ionizing radiation are present.

• The proposed research will have a significant impact on generating electricity by cheap, efficient, environmentally benign non-nuclear fission and non- fossil fuel means