INSTITUTE OF NANO OPTOELECTRONICS
RESEARCH AND TECHNOLOGY (INOR)

4th ISTEC 2020
INTERNATIONAL SCIENCES, TECHNOLOGY AND ENGINEERING CONFERENCE
Exploring Materials for Future

WASEDA University

POWER DEVICES: STATE-OF-THE-ART AND FUTURE PROSPECTS

by **Mohd Syamsul Nasyriq Samsol Baharin**[1,2]

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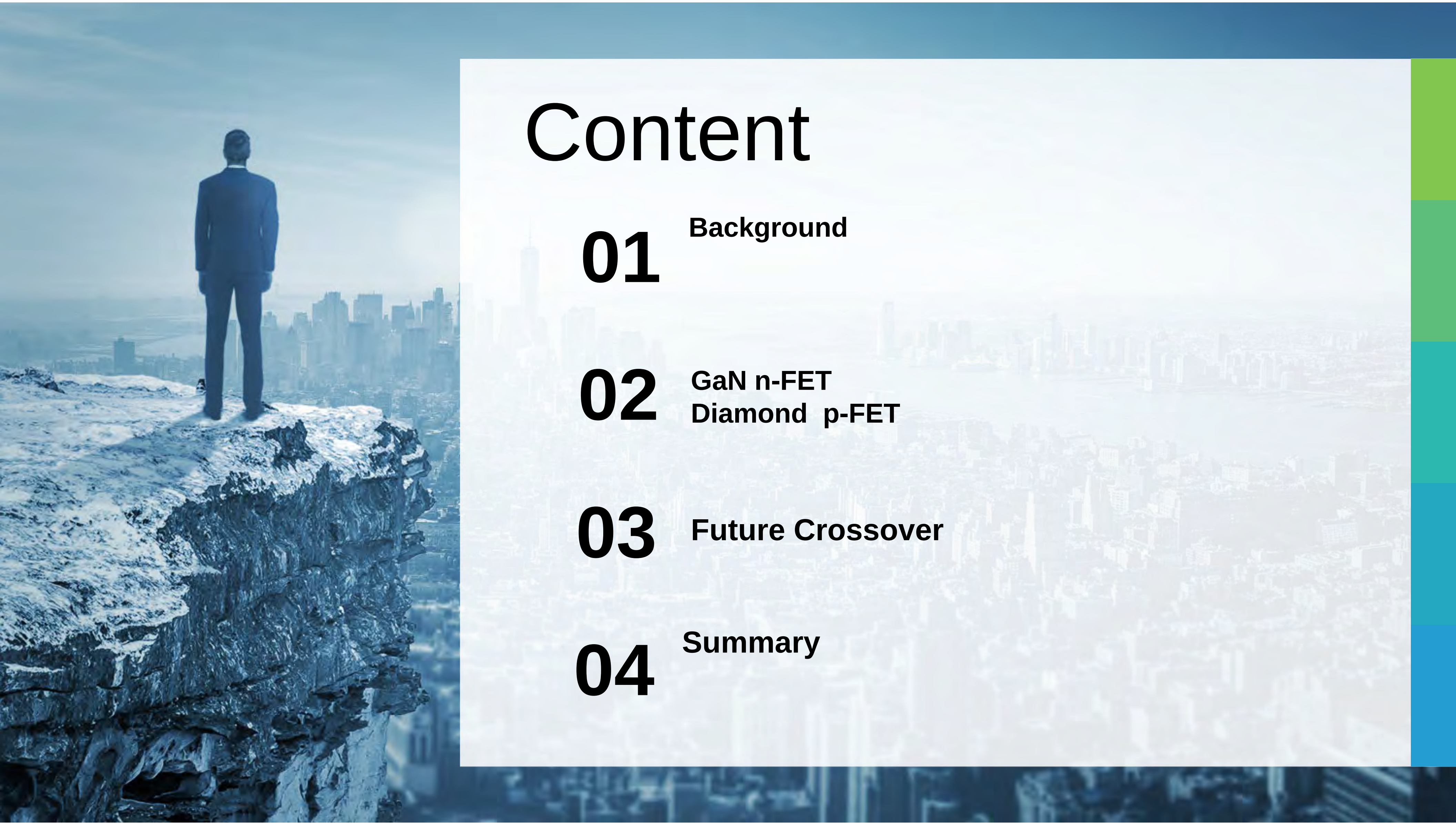
[2]Research Organization for Nano & Life Innovation, Waseda University, 513 Waseda-tsurumaki, Shinjuku, Tokyo 162-0041, Japan



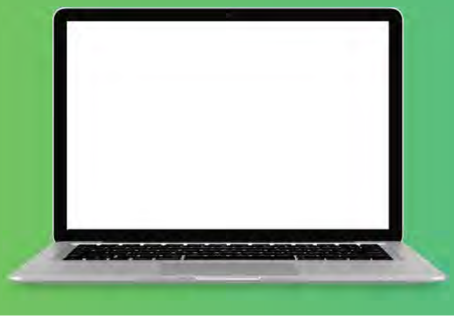
Content

Background

Power devices: Do you know the existence?

Power adapters

- 50% smaller than a standard 61W MacBook charger
- 2.5 times faster than a standard 1A output
- can power up all your USB-C devices, from smart phones to laptops!



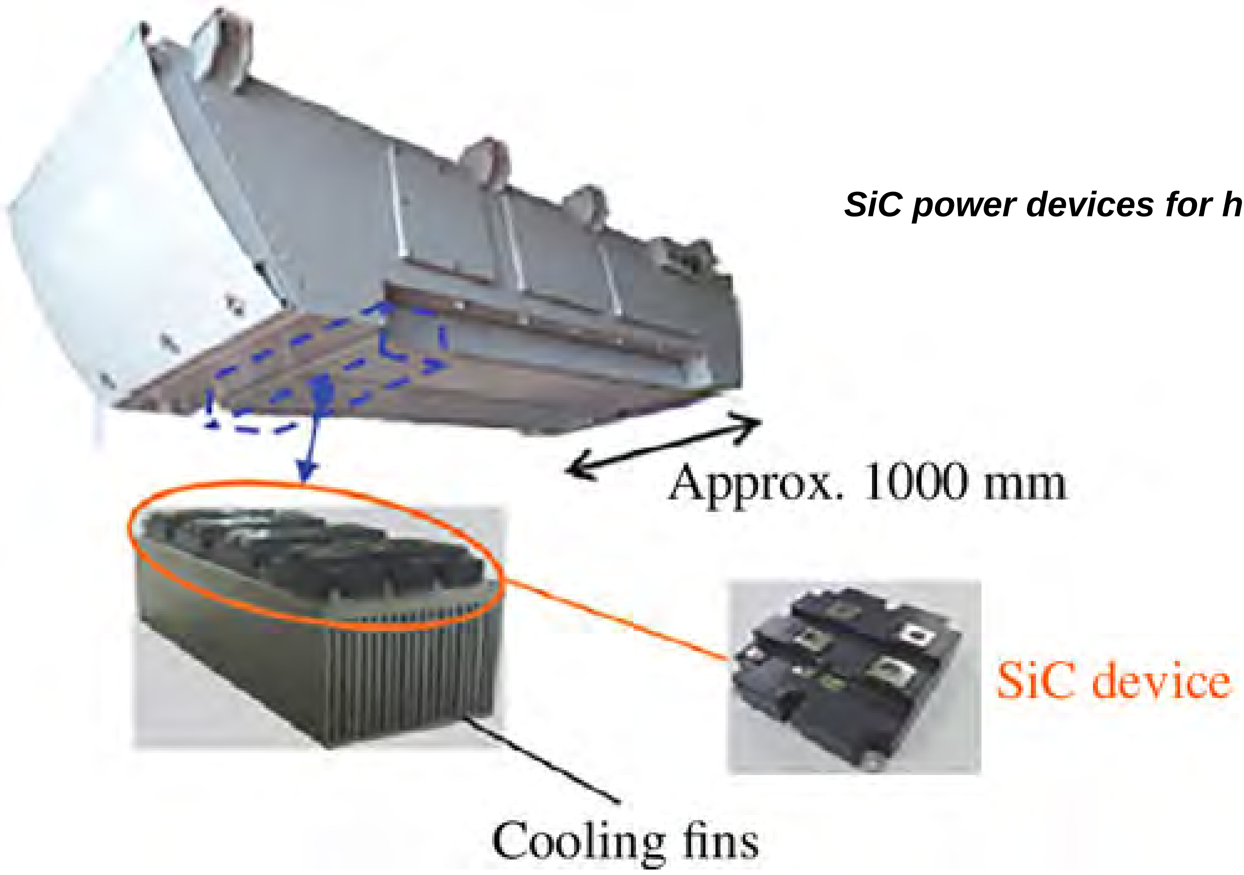
High speed trains

Electric Vehicle

DC/DC converters

Inverters

Why the need of other wide bandgap Power devices?



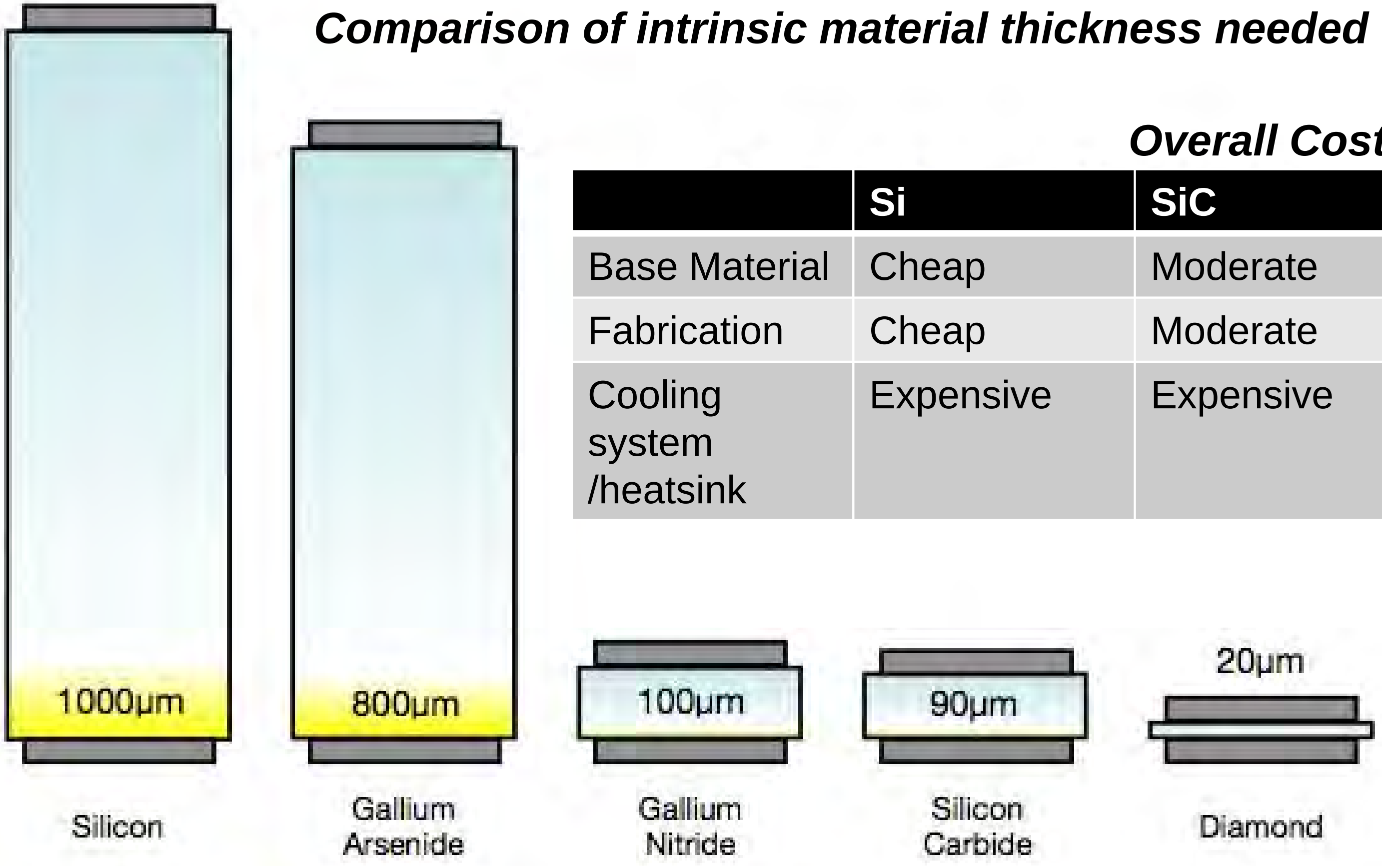
SiC power devices for high-speed train traction

High voltage and thermal capabilities

Comparison of intrinsic material thickness needed to hold-of 10,000V

Overall Costs

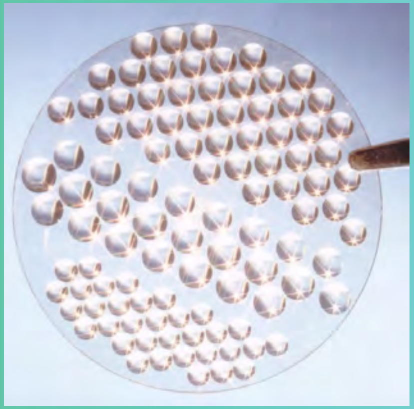
	Si	**SiC**	**GaN**	**Diamond**
Base Material	Cheap	Moderate	Cheap	Moderate
Fabrication	Cheap	Moderate	Moderate	Cheap
Cooling system /heatsink	Expensive	Expensive	Expensive	Cheap



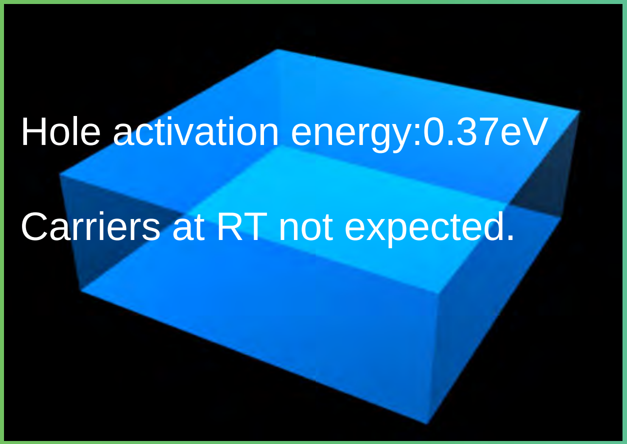
Imagine the size of heatsink required for Diamond!!

Natural Semiconducting Diamonds

Blue diamond
Hope Diamond
(Smithsonian Museum)



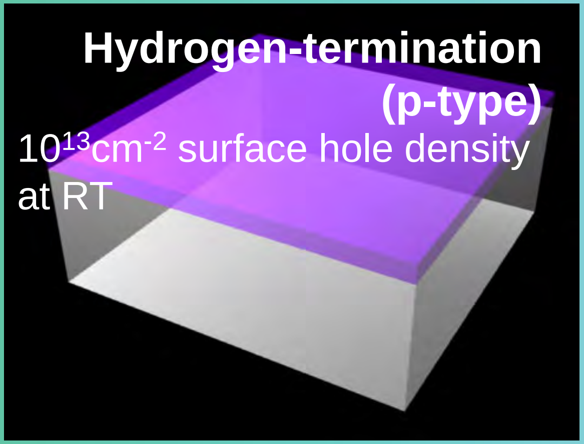
CVD diamond
Poly ~ ϕ150mm
Single ~ ϕ 13mm
Hetero ~ ϕ 100 mm



Hole activation energy:0.37eV

Carriers at RT not expected.

Boron doped diamond (p-type)



Hydrogen-termination (p-type)

10^{13}cm^{-2} surface hole density at RT

CVD diamond (insulating)

Basic physical properties and figure of merits

	Si	GaAs	4H SiC	GaN	Diamond
Bandgap E_G [eV]	1.1	1.43	3.10	3.45	**5.45**
Saturated drift velocity v_S [10^7 cm/s]	1.0	1.0	2.0	2.2	**1.0 (hole)**
Carrier mobility μ [$\mathrm{cm^2/V \cdot s}$]	1500	8500	1140	1250	3800(hole)
Breakdown field E_B [MV/cm]	0.3	0.4	3	2	**~10**
Dielectric constant ε_r	11.8	12.5	9.6/10	9	5.5
Thermal conductivity λ [W/cm·K]	1.5	0.5	4.9	1.3	**22.0**
Johnson's figure of merit [10^{23} $\Omega \cdot \mathrm{W/s^2}$]	2.3	9.1	910	1080	2530(hole)
Keyes' figure of merit [10^7 W/K·s]	6.7	2.0	35	10	145(hole)
Baliga's figure of merit [Si = 1]	1	48	620	600	43938 (hole)

Johnson's figure of merit

Frequency & power products of transistors

$$JFM = \left(\frac{E_B \cdot v_S}{2\pi} \right)^2$$

Keyes' figure of merit

Thermal limitation on high-frequency performance

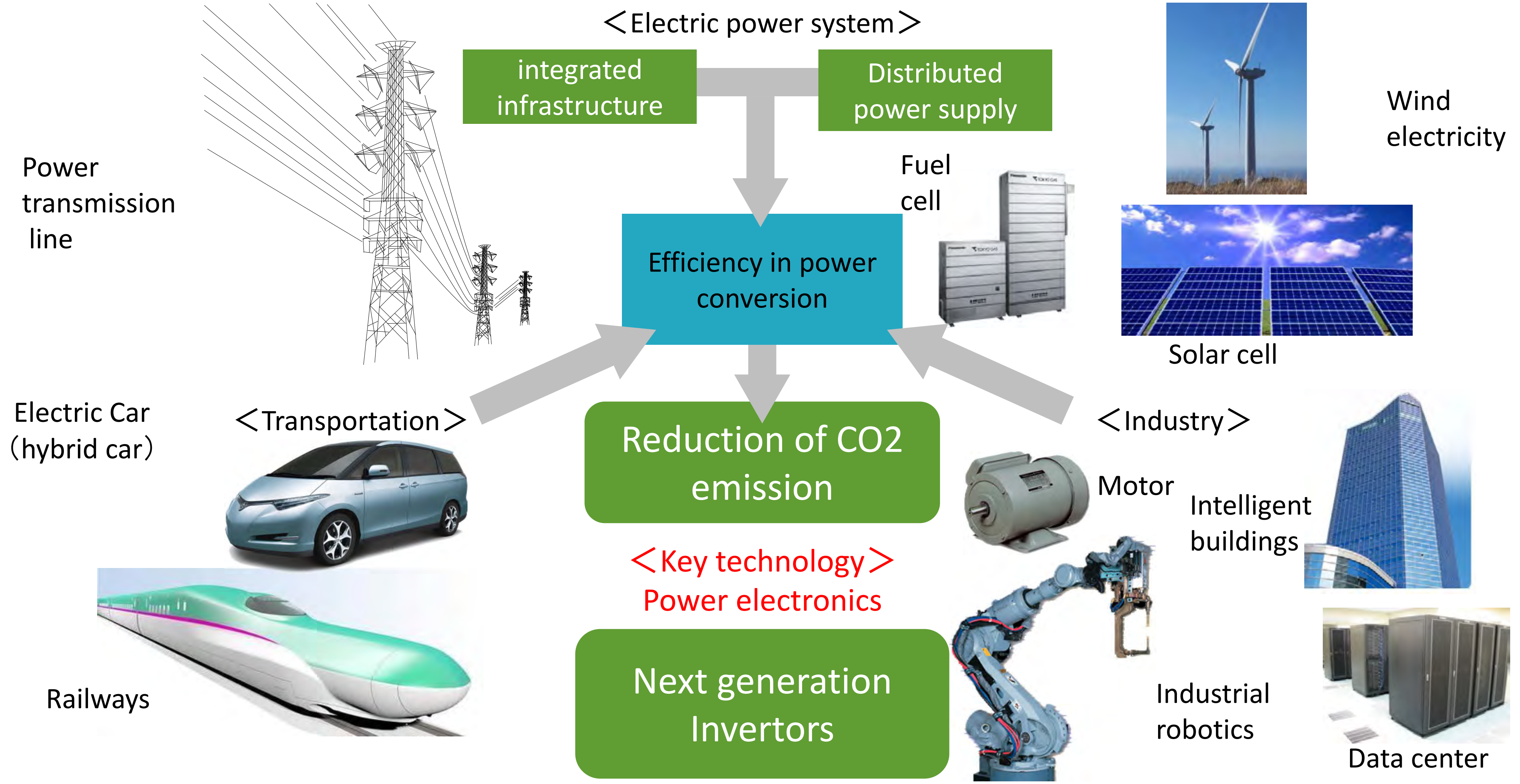
$$KFM = \lambda \left(\frac{c \cdot v_S}{2\pi \cdot \varepsilon_r} \right)^{\frac{1}{2}}$$

Baliga's figure of merit

Loss in high-power & high-frequency operation

$$BFM = \varepsilon \cdot \mu \cdot E_B{}^3$$

Low CO_2 emission by reduction of power loss



＜Electric power system＞

integrated infrastructure

Distributed power supply

Power transmission line

Fuel cell

Wind electricity

Solar cell

Efficiency in power conversion

Reduction of CO2 emission

＜Transportation＞

Electric Car（hybrid car）

Railways

＜Industry＞

Motor

Intelligent buildings

Industrial robotics

Data center

＜Key technology＞
Power electronics

Next generation Invertors

GaN n-FET
Diamond p-FET

Known for pioneering LED research

USM

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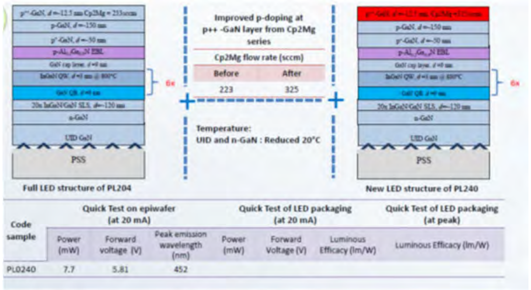
2 inch



Full LED structure of PL204

Improved p-doping at p++ -GaN layer from Cp2Mg series

Cp2Mg flow rate (sccm)	
Before	After
223	325

Temperature:
UID and n-GaN : Reduced 20°C

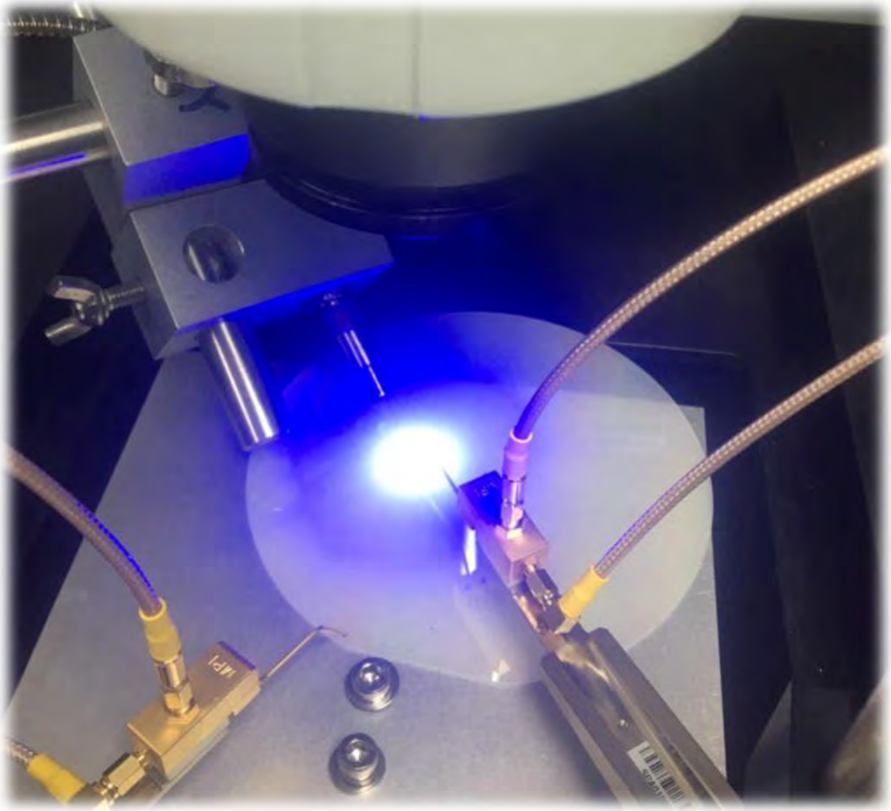
New LED structure of PL240

Code sample	Quick Test on epiwafer (at 20 mA)			Quick Test of LED packaging (at 20 mA)			Quick Test of LED packaging (at peak)
	Power (mW)	Forward voltage (V)	Peak emission wavelength (nm)	Power (mW)	Forward Voltage (V)	Luminous Efficacy (lm/W)	Luminous Efficacy (lm/W)
PL0240	7.7	5.81	452				

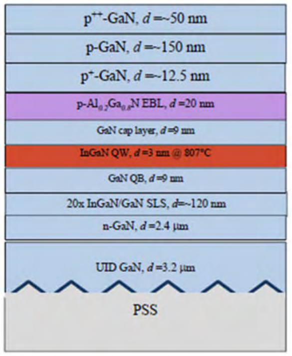
CREST
COLLABORATIVE RESEARCH IN ENGINEERING, SCIENCE & TECHNOLOGY

OSRAM
Opto Semiconductors

UCSB



4 inch



p^{++}-GaN, d =~50 nm
p-GaN, d =~150 nm
p^{+}-GaN, d =~12.5 nm
p-$Al_{0.2}Ga_{0.8}N$ EBL, d =20 nm
GaN cap layer, d =9 nm
InGaN QW, d =3 nm @ 807°C
GaN QB, d =9 nm
20x InGaN/GaN SLS, d=~120 nm
n-GaN, d =2.4 µm
UID GaN, d =3.2 µm
PSS

GaN on GaN Programme supported by Ministry of Economic Affairs since 2015-2020

Improving structure for better lm/W

Preliminary power device studies

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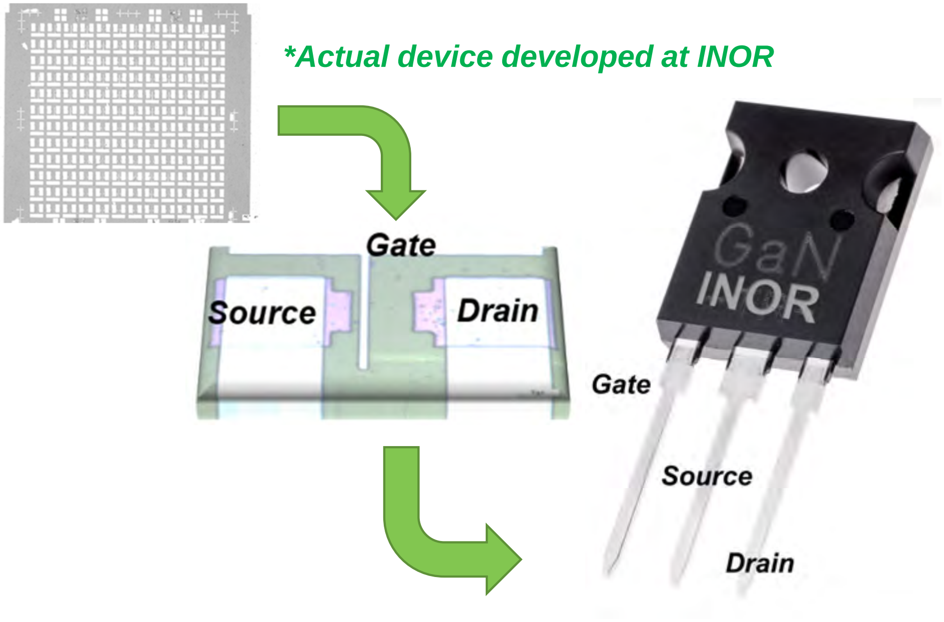
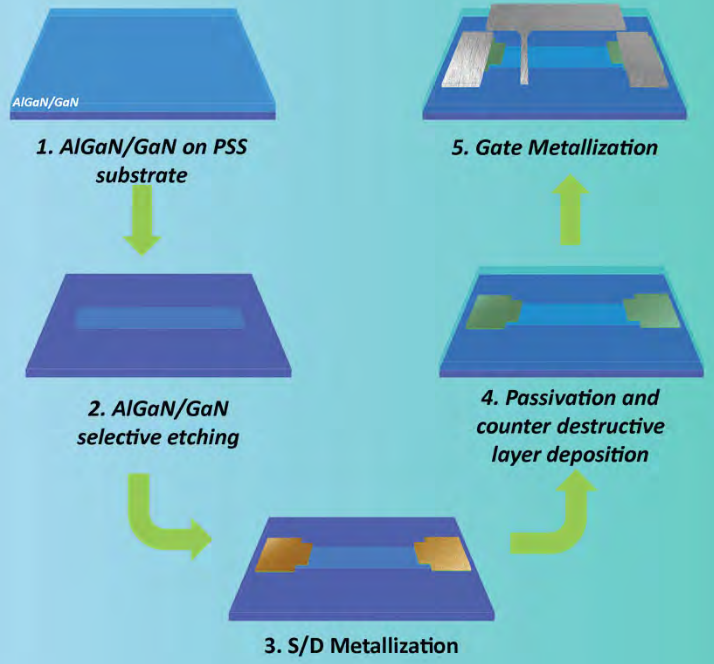
The first GaN-based power device developed in Malaysia

Metal Organic Chemical Vapor Deposition (MOCVD)

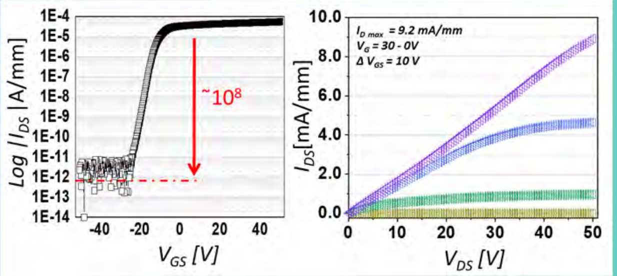


**Actual device developed at INOR*

Detailed proof of concept

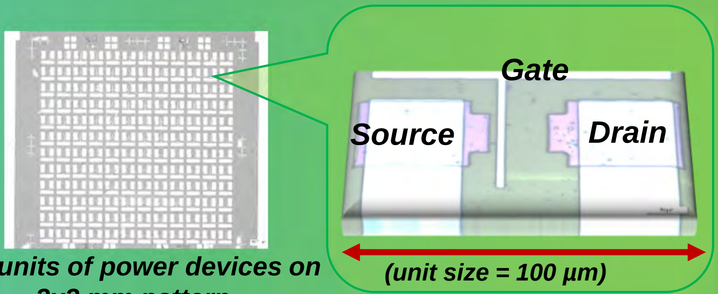


1. AlGaN/GaN on PSS substrate
2. AlGaN/GaN selective etching
3. S/D Metallization
4. Passivation and counter destructive layer deposition
5. Gate Metallization



Transfer Characteristics

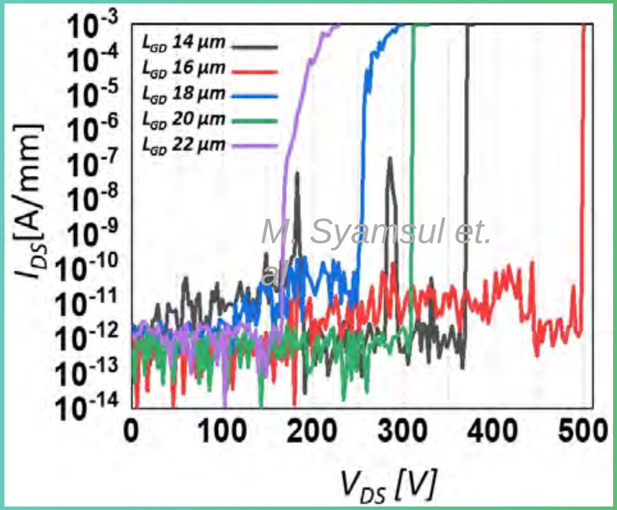
GaN power device structure

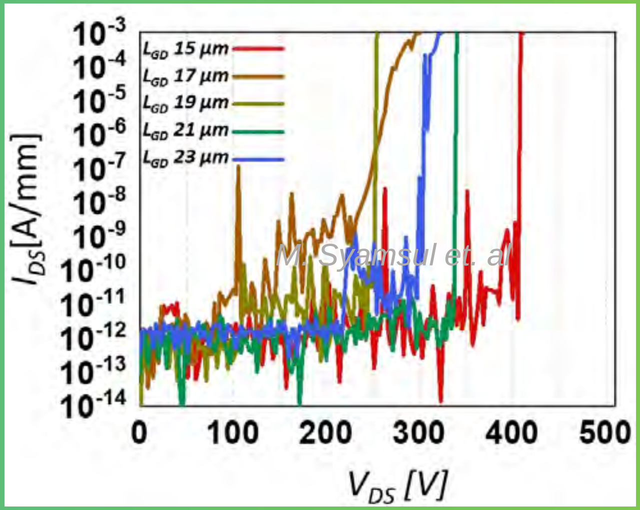


122-units of power devices on 3x3 mm pattern

*Actual device developed at INOR

Pencirian elektrik

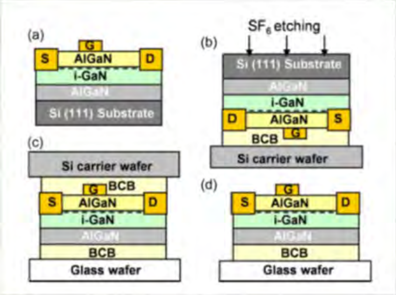


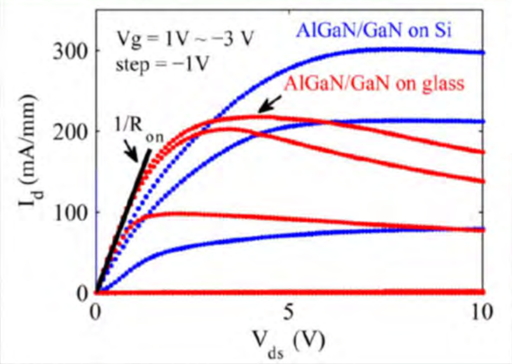


Electrical characteristics for 10 units of GaN power device achieving 500 V

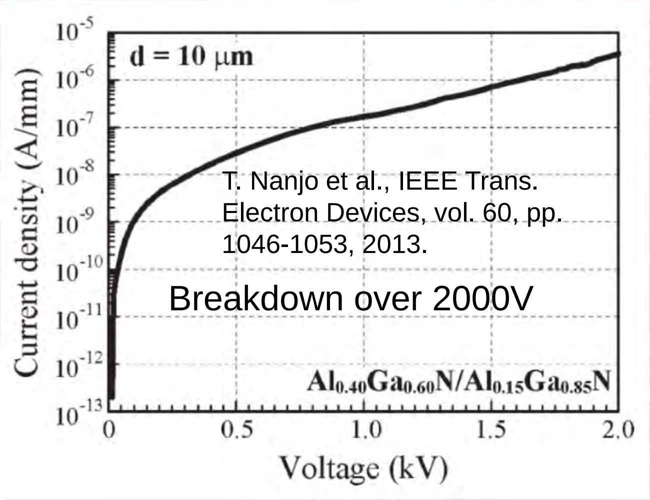
GaN Devices - *matured*

Breakdown over 1500V



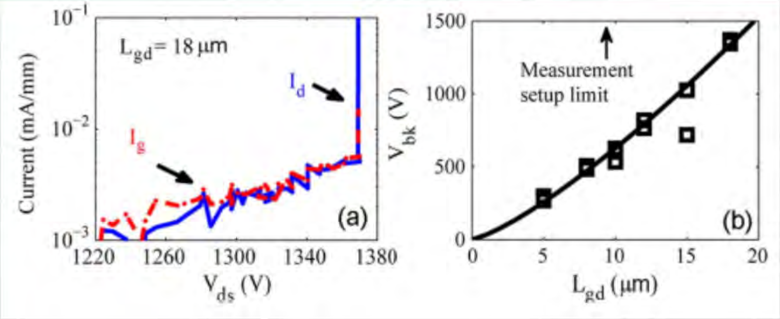


B. Lu, T. Palacios, Electron Device Letters IEEE, vol. 31, no. 9, pp. 951-953, 2010.

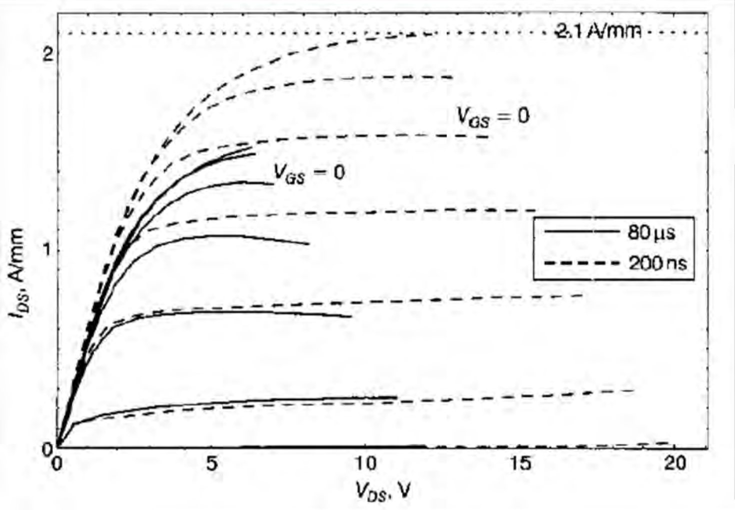


T. Nanjo et al., IEEE Trans. Electron Devices, vol. 60, pp. 1046-1053, 2013.

Breakdown over 2000V

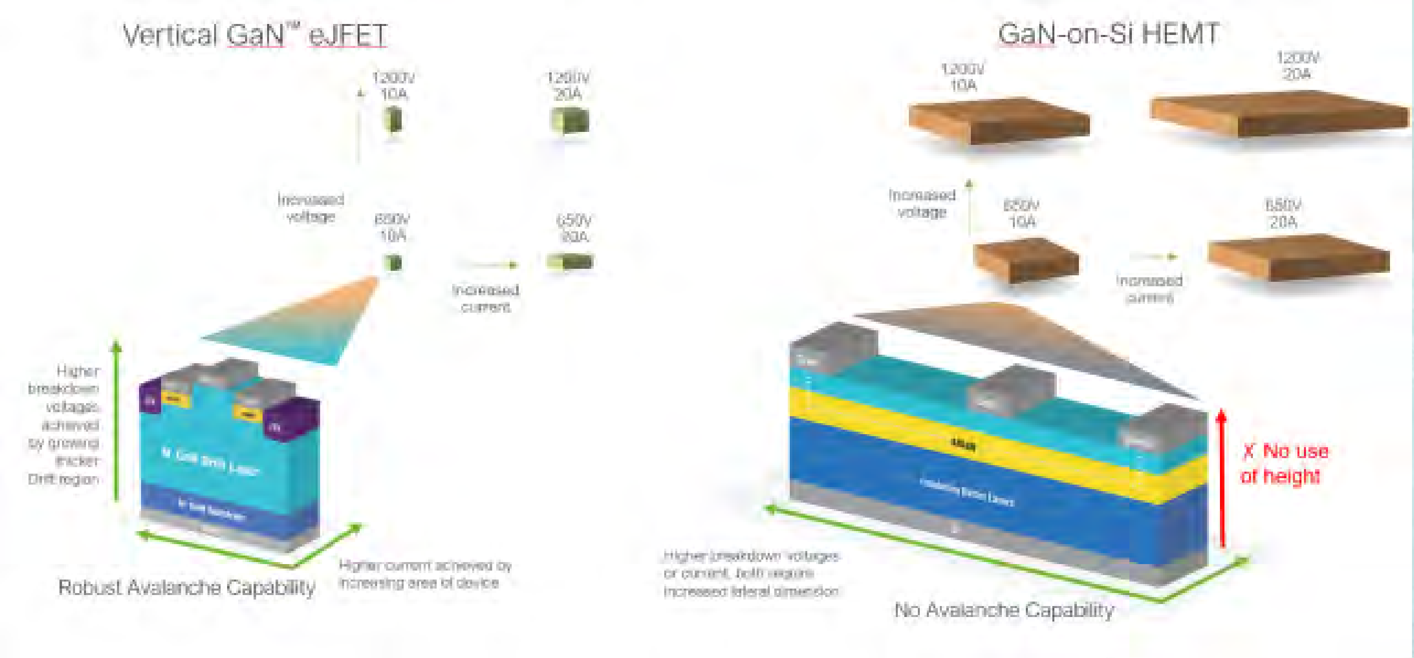


Idmax 2.1 to 2.3 A/mm

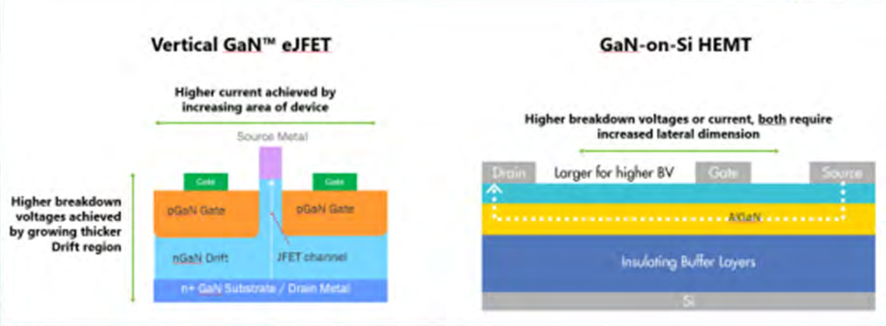


T. Zimmermann, D. Deen, Y. Cao, J. Simon, P. Fay, D. Jena and H. G. Xing, IEEE Electron Device Lett. 29, 7 (2008).

GaN Devices - *matured*

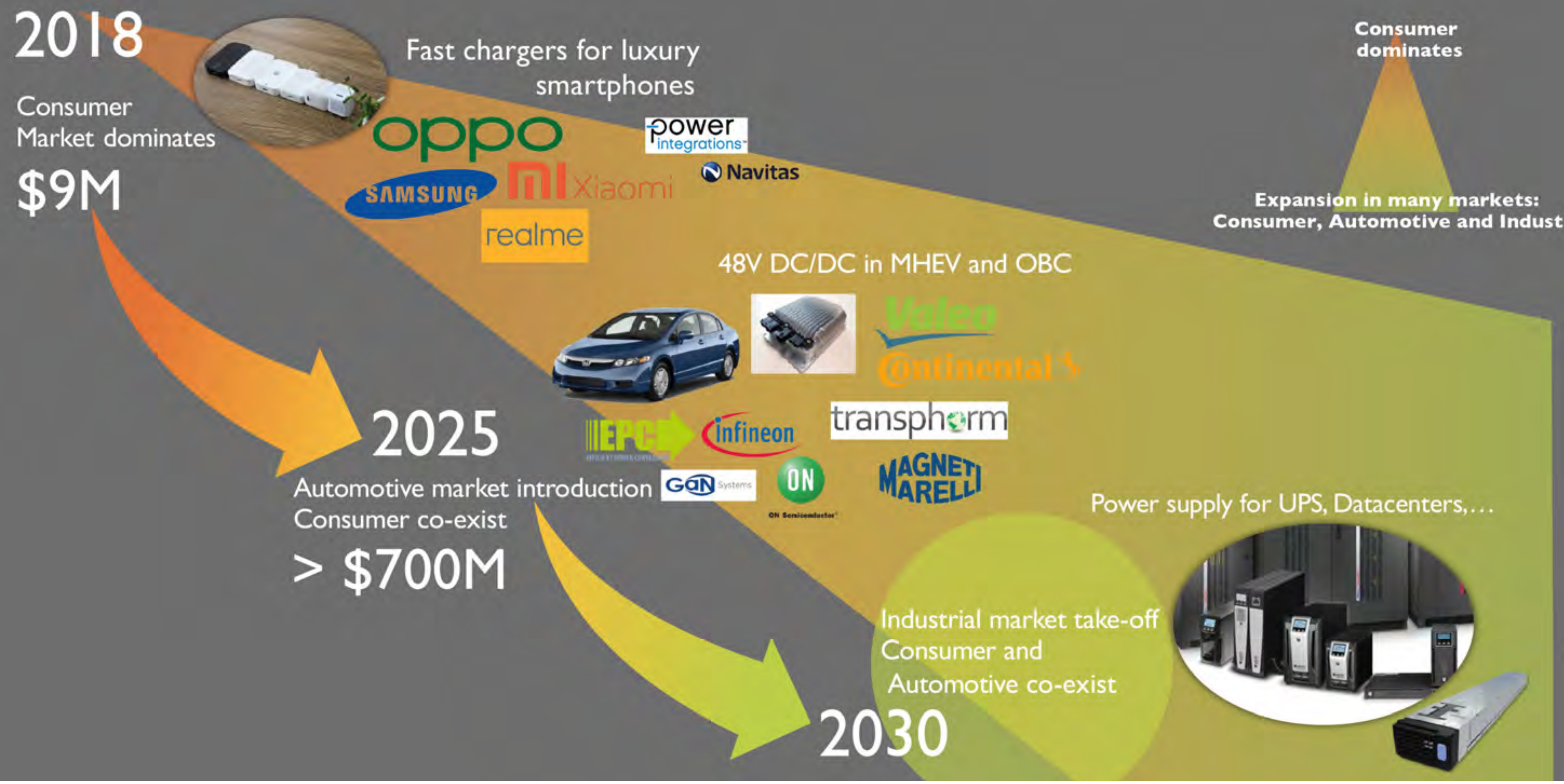


NextGen Power System



Entering a new era

(Source: Compound Semiconductor Quarterly Market Monitor, Yole Développement, March 2020)



2018

Consumer
Market dominates

$9M

Fast chargers for luxury
smartphones

48V DC/DC in MHEV and OBC

2025

Automotive market introduction
Consumer co-exist

> $700M

Power supply for UPS, Datacenters,…

Industrial market take-off
Consumer and
Automotive co-exist

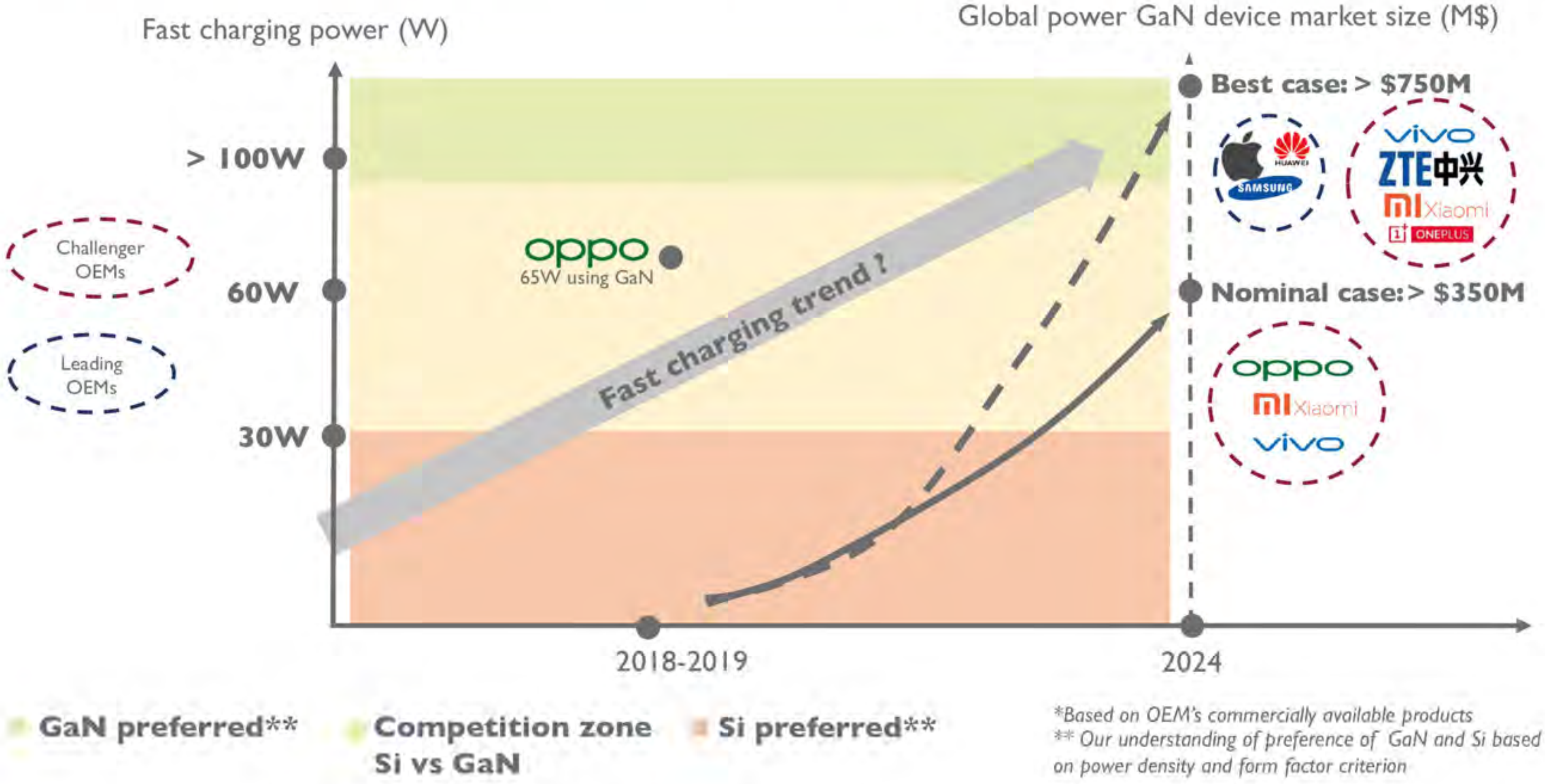
2030

Consumer dominates

Expansion in many markets:
Consumer, Automotive and Industrial

2018-2024 power GaN device market driven by high-power fast charging applications*

(Source: Power GaN 2019: Epitaxy, Devices, Applications & Technology Trends report, Yole Développement, 2019)



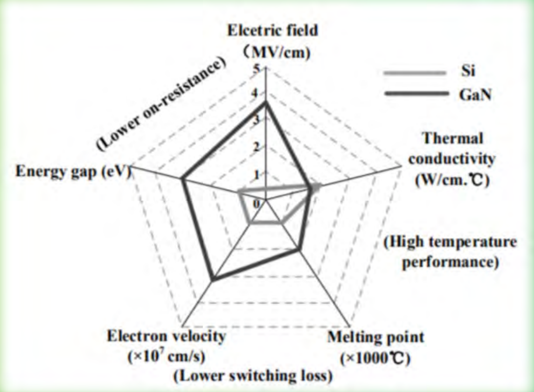
*Based on OEM's commercially available products

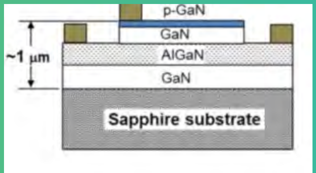
** Our understanding of preference of GaN and Si based on power density and form factor criterion

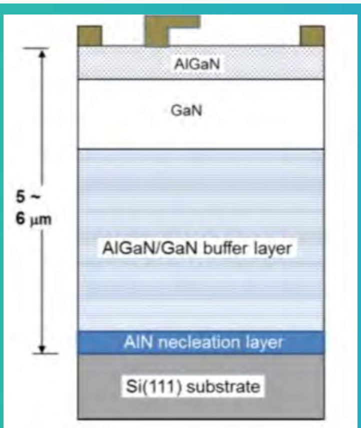
Why GaN on sapphire?

Difference between sapphire and silicon substrate

	Sapphire	Silicon
GaN growth duration	~2 jam	~10 to 12 hours Low Cost
Thickness	1 µm	5~6 µm Low Cost
Reactor cleaning for each growth to avoid contamination/unwanted chemical reaction	None	Needed Low Cost
Growth rate	10 times higher	Normal Low Cost







Growth time, rate and thickness for GaN growth on Silicon substrate is high, thus requires high usage/cost for consumables, electricity,gases and longer time.

1.Microwave and High Power devices
and their characteristics

-Diamond MOSFET

f_T 45 GHz, V_B 1500V

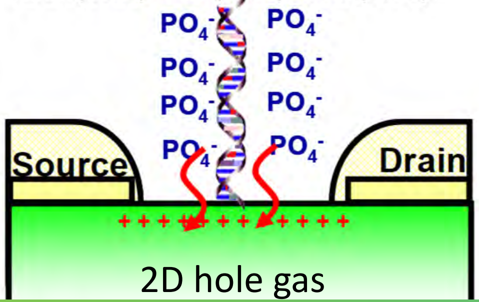
IEEE Elect. Dev. Lett, **22**, 390 (2001)
23, 121(2002), **25**, 480(2004)
IEEE IEDM (2007) **IEDM (2014) ISPSD (2016)**
IEEE TED (2010), APEX (2010), JJAP (2012), APL (2014)
IEEE EDL (2017) ScRep(2017)

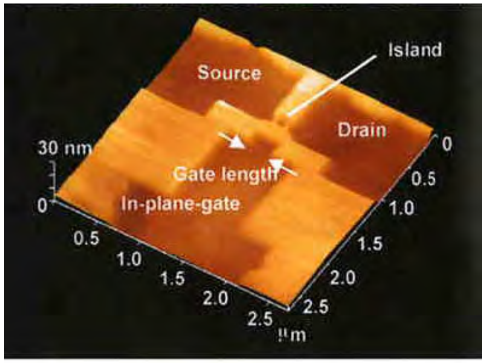
3. Biosensor & bioelectronics

-Surface chemical modification

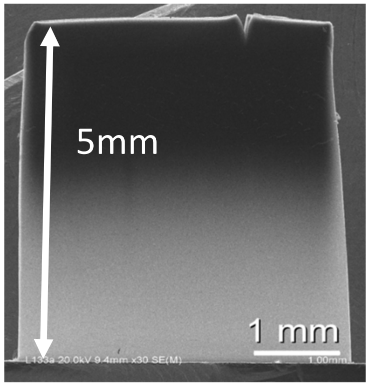
-Diamond solution gate FETs
for Biosensing DNA detection

Phys.Rev.E. **74**, 041919 (2006)
Appl. Phys. Lett. **90**, 063901 (2007) .
J. Am.Chem Soc. 130,13251(2008)
IEEE IEDM pp. (2008)
Biosensor & Bioelect (2010), (2012), (2013)
APEX (2011) PRB (2014) PRB (2016)





Appl. Phys. Lett., **81**, 2854 (2002).



2.Superconductivity
and transistor application

Highly B-doped >10^{21}cm^{-3}
Diamond Tc ~10K

Cryoelectronics

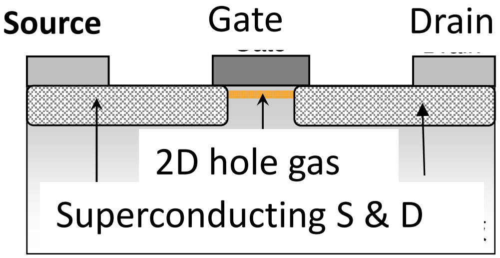
Y.Takano, H. Kawarada, et al.
Appl. Phys. Lett. (2004)
T. Yokoya, H. Kawarada, et al. Nature,
438, 647 (2005)
Phys. Rev. B 81 045303 (2010)
Phys.Rev. B 85 184516 (2012) APL (2015)

WASEDA University

State of art plasma deposition

4. Carbon nanotubes:
Densely packed & vertically aligned
single or double wall CNTs for interconnection and super capacitor

J. Phys. Chem. B, **109**, 19556 (2005)
Carbon, **44**, 2009 (2006)
J. Phys. Chem. B, **111**, 1907 (2007)
Nano Letters 8 886 (2008) , **Carbon (2010), (2012), (2013)**



Carbon based nano and bioelectronics

Is diamond expensive?

Diamond Synthesis from natural gas CH_4 and green house gases CO_2, CO, CH_4

CH_4 Natural Gas

CO_2、CO from exhaust gas

Source: natural gas CH_4,
green house gas CO_2

$CH_4 + CO_2 \rightarrow \underline{\mathbf{2C}} + 2H_2O$ by product is “Water”

Diamond

Using natural gas CH_4, exhaust gas CO_2 and their recycling and electrical power from power plant

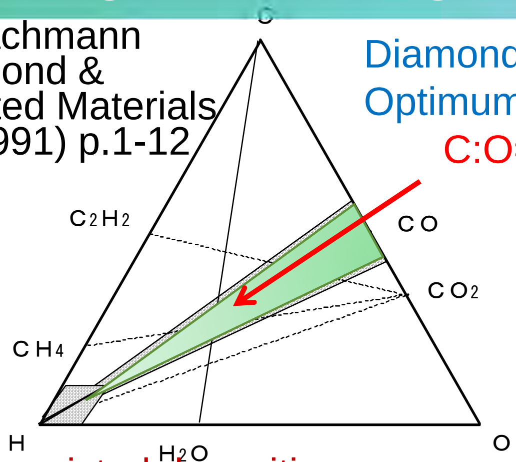
Cost of single crystal diamond wafer

1 cm^2	＄9
2 inch	＄180

Manpower, electric power, gas, polishing, recycling of substrate ~40%

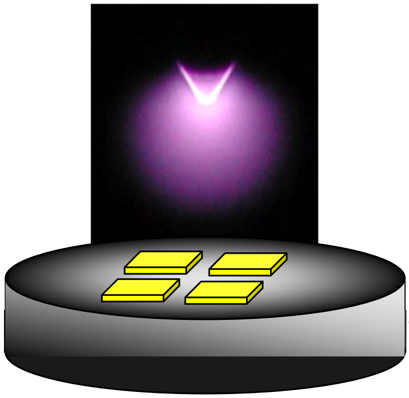
Plasma reactor ~60%

P. Bachmann
Diamond &
Related Materials
1 (1991) p.1-12

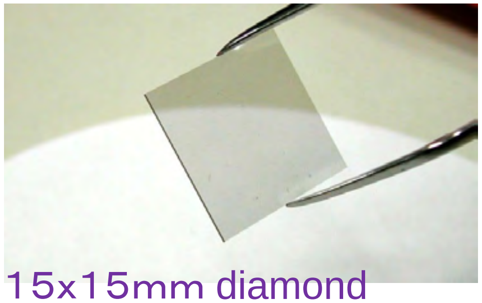


Diamond Synthesis
Optimum gas ratio
C:O=1:1

Plasma assisted deposition



CH4 plasma

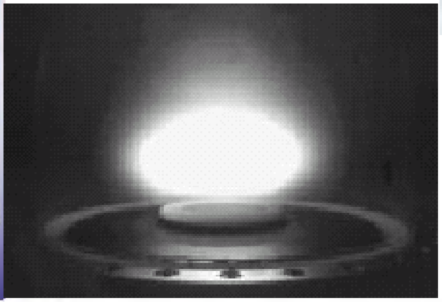


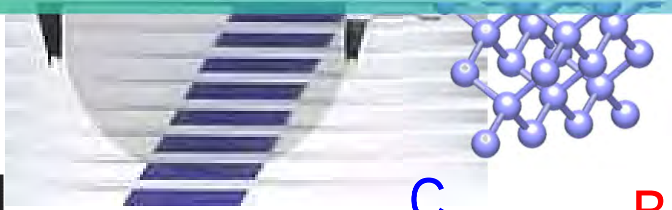
15x15mm diamond from 4 inch diamond wafer

Same price as GaN substrates!

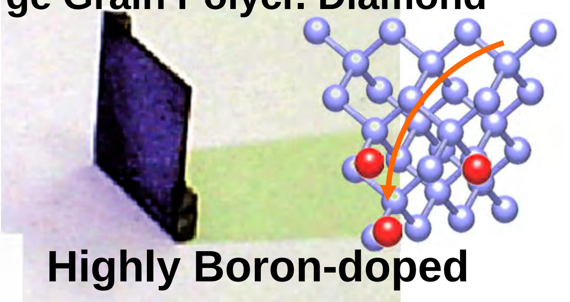
CVD Diamond Single 1 inch, Transparent 4inch with High FET Performance

Carbon Dioxide CO_2
Hydrogen H_2
Plasma Assisted CVD



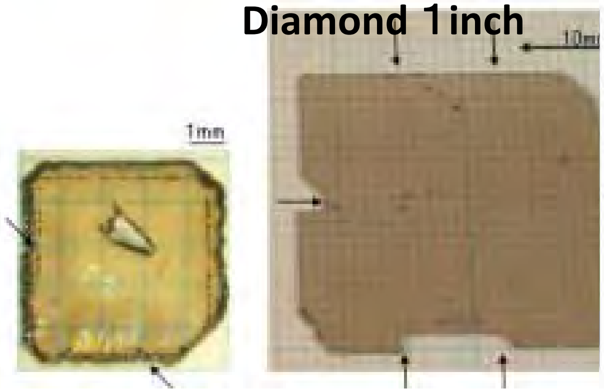


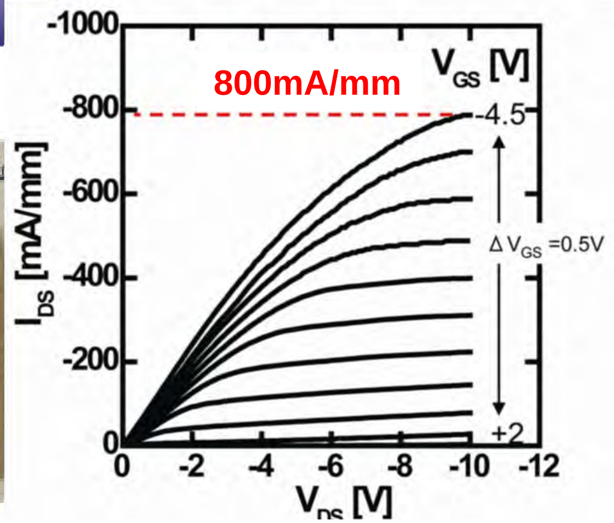
Large Grain Polycr. Diamond



Highly Boron-doped
CVD Diamond Resistivity
$<10^{-3}\Omega cm \rightarrow$ Superconductor

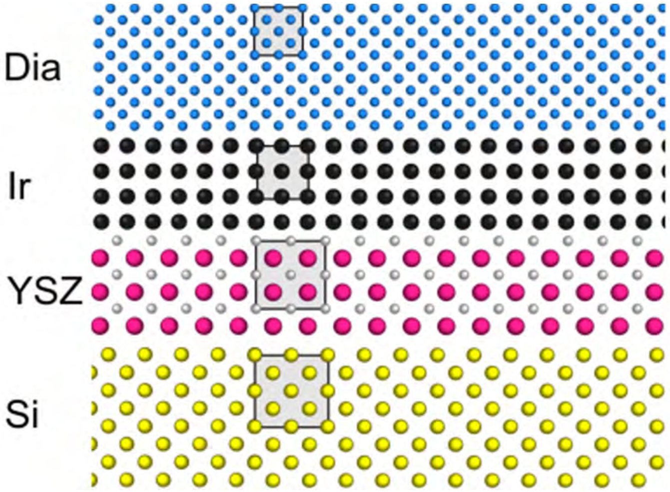
Homoeptaxial
Diamond 1 inch



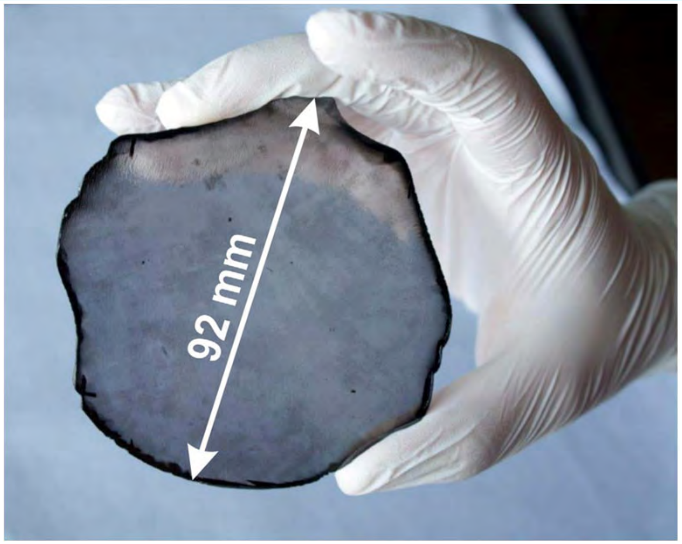


Transparent
Polycrystalline Diamond
FET
$I_{D\ Max}$ 0.8A/mm
f_T 45GHz
(IEDM 2007, p.873)

Heteroepitaxial diamond on Ir(001) on Si(001) substrate



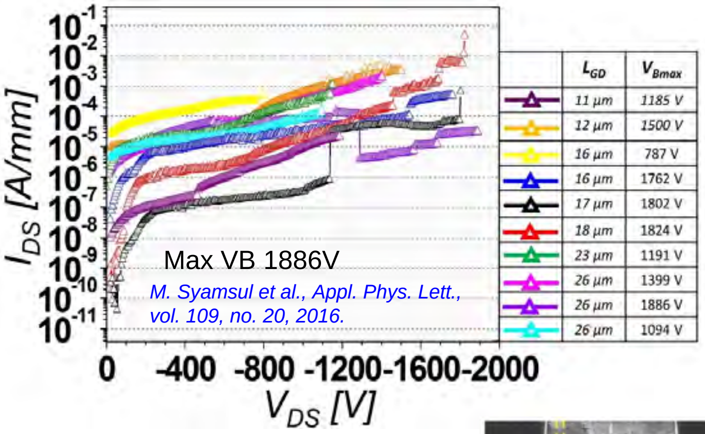
Heteroepitaxial diamond starts with a Si substrate. The Yttria-stabilized zirconia (ZrO_2), YSZ, keeps the Ir from reacting with the Si substrate.



Free standing 31g, 3.6-inch diameter unpolished diamond single crystal synthesized by heteroepitaxy on Ir/YSZ/Si(001).

M. Schreck, S. Gsell, R. Brescia, M. Fischer, Sci. Rep. 7, 44462 (2017)
University Augusburg and its venture company

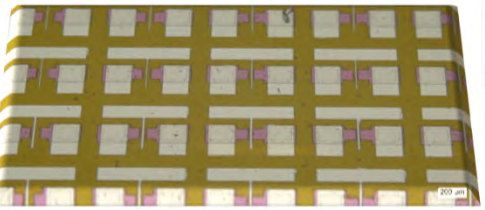
Black polycrystalline diamond FET

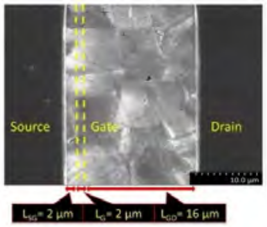


	L_{GD}	V_{Bmax}
△	11 µm	1185 V
△	12 µm	1500 V
△	16 µm	787 V
△	16 µm	1762 V
△	17 µm	1802 V
△	18 µm	1824 V
△	23 µm	1191 V
△	26 µm	1399 V
△	26 µm	1886 V
△	26 µm	1094 V

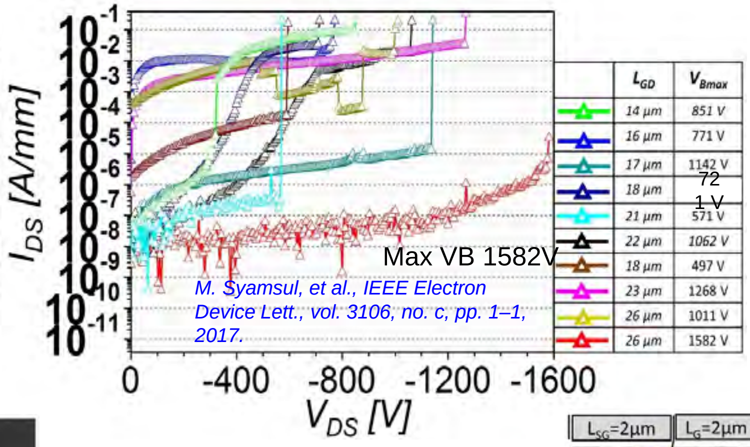
Max VB 1886V

M. Syamsul et al., Appl. Phys. Lett., vol. 109, no. 20, 2016.





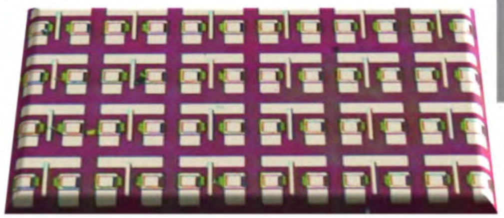
Transparent polycrystalline diamond FET

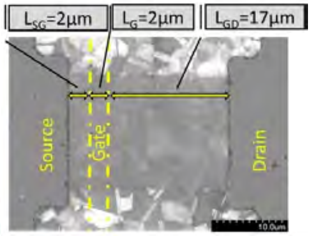


	L_{GD}	V_{Bmax}
△	14 µm	851 V
△	16 µm	771 V
△	17 µm	1142 V
△	18 µm	72 1 V
△	21 µm	571 V
△	22 µm	1062 V
△	18 µm	497 V
△	23 µm	1268 V
△	26 µm	1011 V
△	26 µm	1582 V

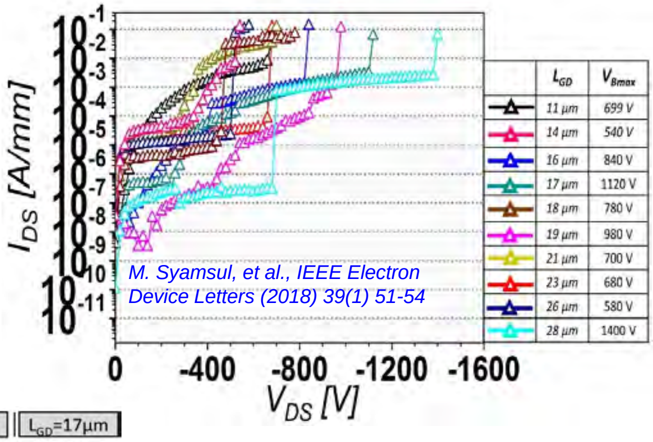
Max VB 1582V

M. Syamsul, et al., IEEE Electron Device Lett., vol. 3106, no. c, pp. 1–1, 2017.



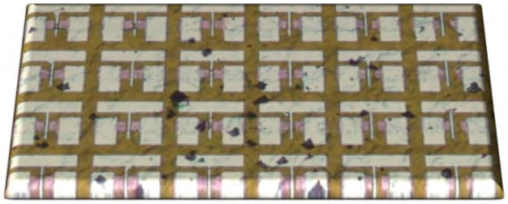


Heteroepitaxial diamond FET



	L_{GD}	V_{Bmax}
△	11 µm	699 V
△	14 µm	540 V
△	16 µm	840 V
△	17 µm	1120 V
△	18 µm	780 V
△	19 µm	980 V
△	21 µm	700 V
△	23 µm	680 V
△	26 µm	580 V
△	28 µm	1400 V

M. Syamsul, et al., IEEE Electron Device Letters (2018) 39(1) 51-54

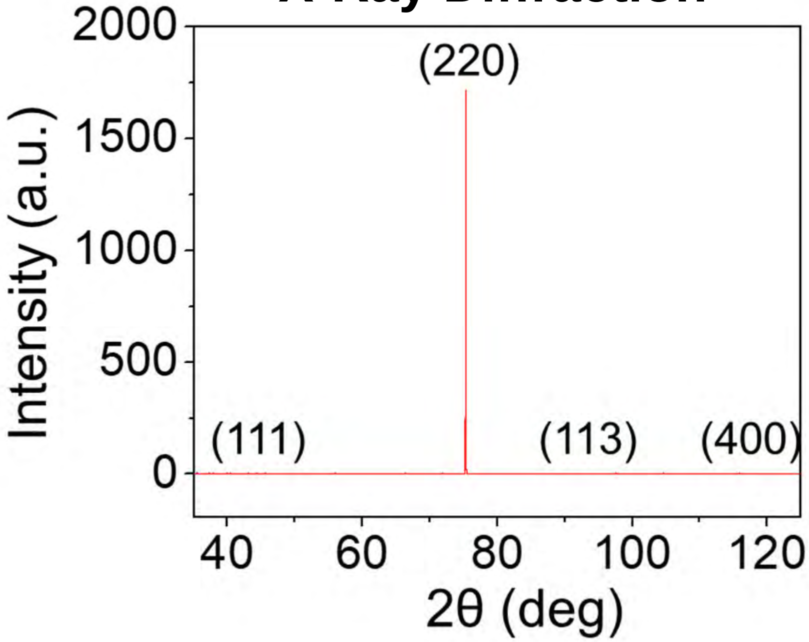


Polycrystalline diamonds and heteroepitaxial diamonds

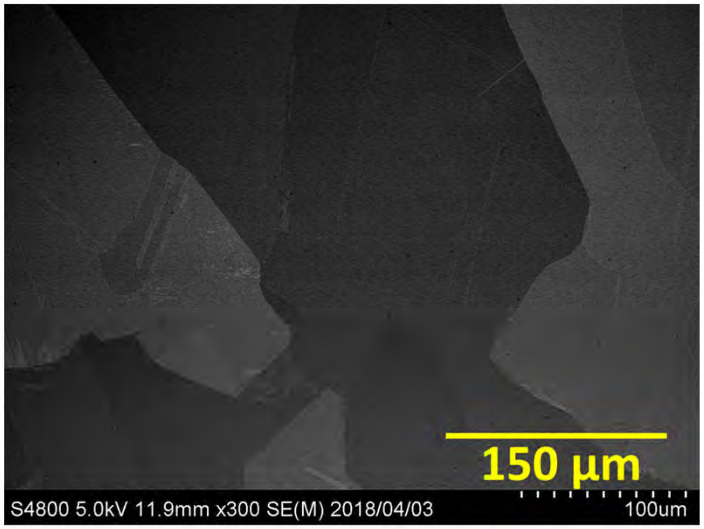
IIa-type polycrystalline diamond substrate

Substrate size: 5 × 5 × 0.5 mm

X-Ray Diffraction



SEM Image



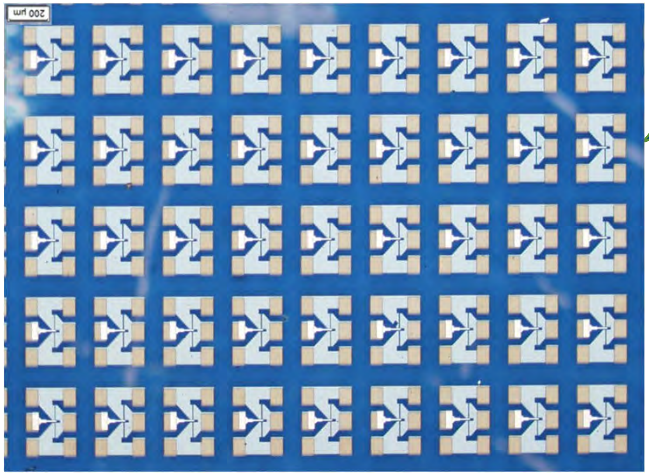
Grain size ~ 300 µm

MRS 2018 Fall EP08,
EP09 Wed 11:45
Imanishi, HK

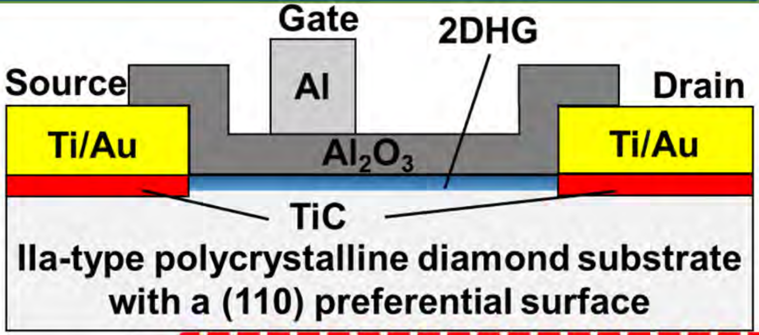
The IIa-type polycrystalline diamond substrate has a (110) preferential surface.

ALD-Al2O3 2DHG Diamond MOSFET

Imanishi, HK , IEEE EDL (early access 2018)



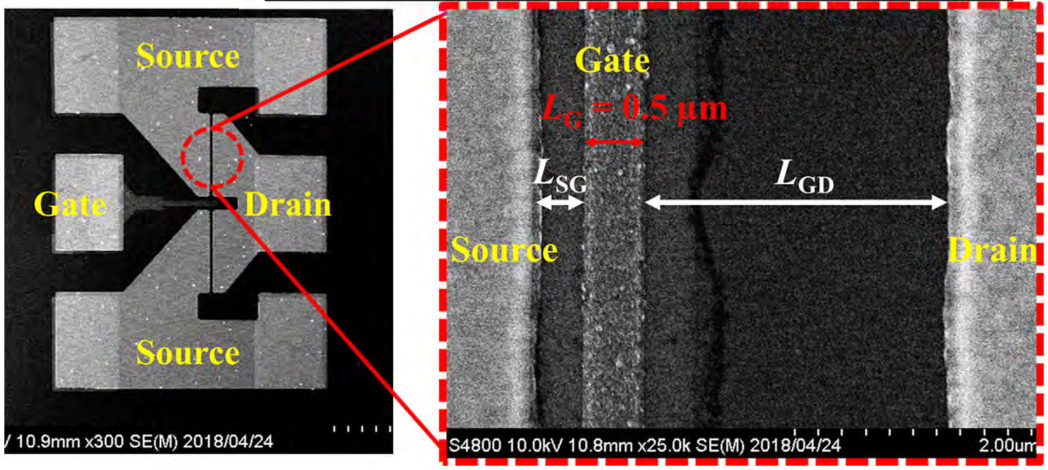
The operation of **93%** devices was confirmed.



K. Ueda, M. Kasu: Diamond and related materials ***15*** *(2006) 1954.*

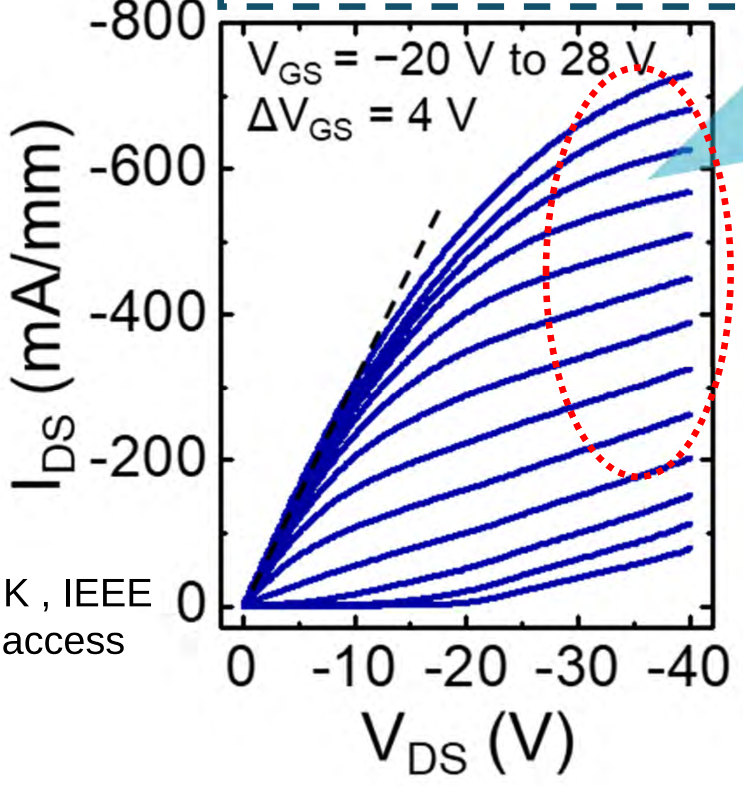
Device dimensions

- L_{SG} = 0.5 μm
- L_G = 0.5 μm
- L_{GD} = 1 ~ 3 μm
- W_{ch} = 100 μm
- Al_2O_3 thickness = 100 nm



DC Performance on poly (110)

L_{SG} = 0.5 μm, L_G = 0.5 μm, L_{GD} = 1 μm, W_{ch} = 100 μm

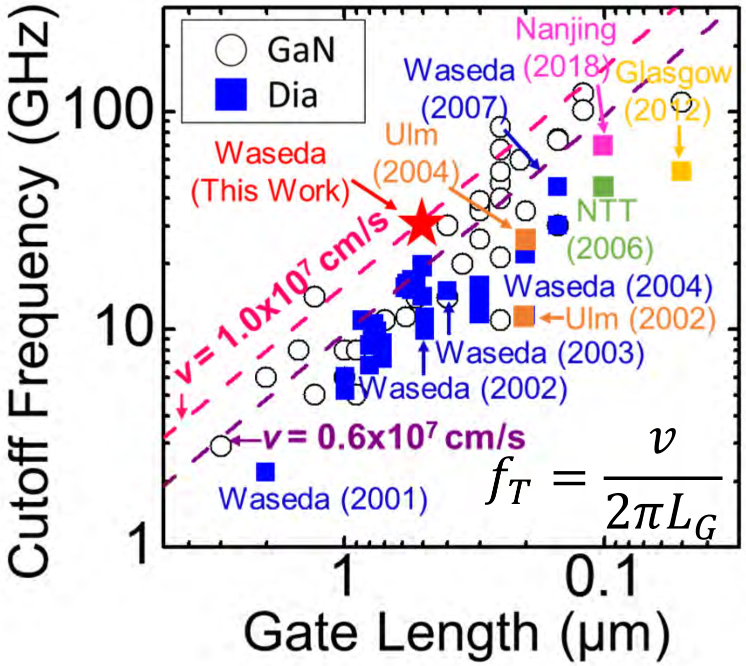


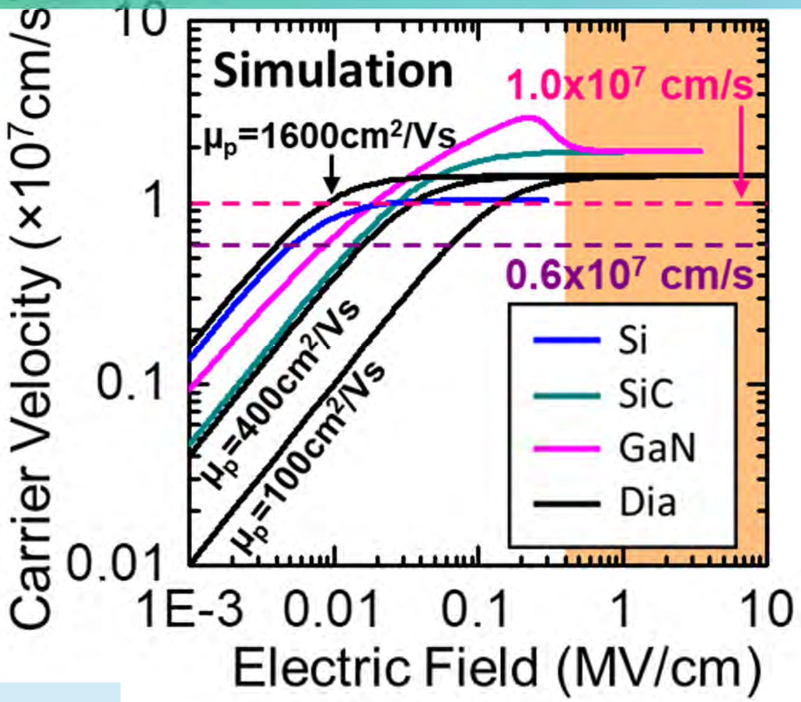
Imanishi, HK , IEEE EDL (early access 2018)

Current collapse was not observed
→High heat dissipation due to high thermal conductivity of diamond

$I_{DS\ MAX}$ = −730 mA/mm
(V_{GS} = −20 V, V_{DS} = −40 V)
g_m ~ 15 mS/mm
(−20 ≦ V_{GS} ≦ 16 V, V_{DS} = −40 V)
$R_{ON\ min}$ = 30 Ω mm
(V_{GS} = −20 V, low V_{DS})

Overview of RF H-terminated diamond FETs





- IEEE EDL 2001, H. Taniuchi, HK. MESFET **2.2GHz**
- IEEE EDL 2002, H. Umezawa, HK. MISFET **15GHz**
- DRM 2004, A. Aleksov, M. Kasu, E. Kohn. MESFET **24GHz**
- IEEE EDL 2004, H. Matsudaira, HK. MISFET **23GHz**
- IEEE EDL 2005, K. Ueda, M. Kasu. MESFET **45 GHz**
- IEDM 2007, K. Hirama, HK. MOSFET**45GHz**
- IEEE EDL 2012 S.A. Russell, D.A. Moran. MESFET **53GHz**
- IEEE EDL 2018, X. Yu, T. Chen. MOSFET **70GHz**

Issue

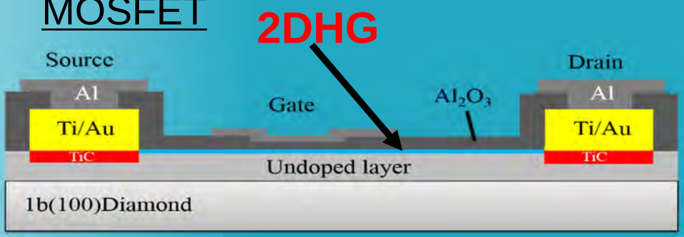
- **Carrier velocity of diamond FETs ≤ 0.6×10^7cm/s**

Future Crossover

2D Hole Gas:Diamond ⇔ 2D Electron Gas:GaN

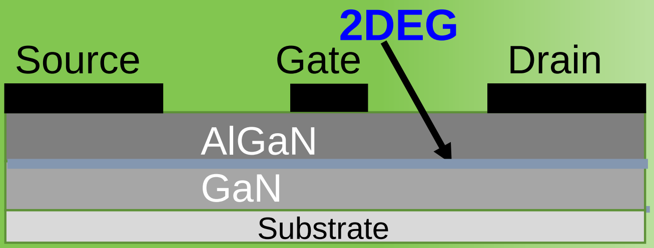
- Similar to the HEMT structure

C-H diamond
MOSFET



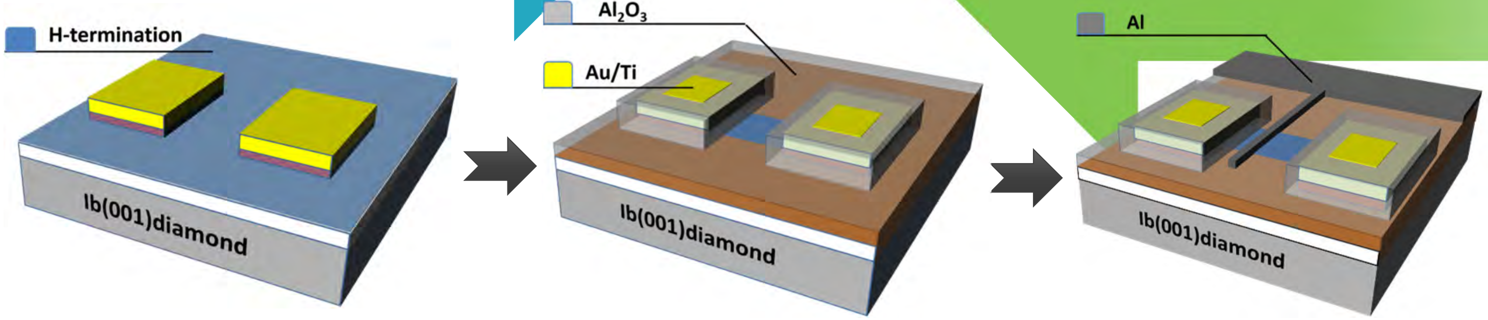
- Using 2 dimensional hole gas

AlGaN/GaN HEMT



- Using 2 dimensional electron gas

Fabrication process



- Deposit Ti/Au electrodes and form TiC by annealing
- H-termination by plasma

- Isolate by O-termination
- Deposit Al_2O_3 by ALD

- Deposit gate electrode (Al)

Comparison with the lateral FETs of SiC, GaN, Ga_2O_3 and Diamond

Types	Maximu drain current density	V_B Break down voltage	L_{GD} Gate-Drain length	V_B / L_{GD} Average electric field strength
SiC [1]	90mA/mm	1600 V	20 μm	0.8 MV/cm
AlGaN/GaN [2]	300mA/mm	200 - 1400 V	4 - 20 μm	1 MV/cm
AlGaN/AlGaN[3]	200mA/mm	500 -1700 V	3 - 15 μm	1.7 MV/cm
Ga_2O_3 [4]	80mA/mm	760 V	15 μm	0.5 MV/cm
C-H Diamond p-FET	110mA/mm (normally on) 18mA/mm (normally off)	365-1700 V 1700-2020 V	1 - 16 μm 20-24 μm	Max 3.7 MV/cm ~1 MV/cm ~0.8MV/cm

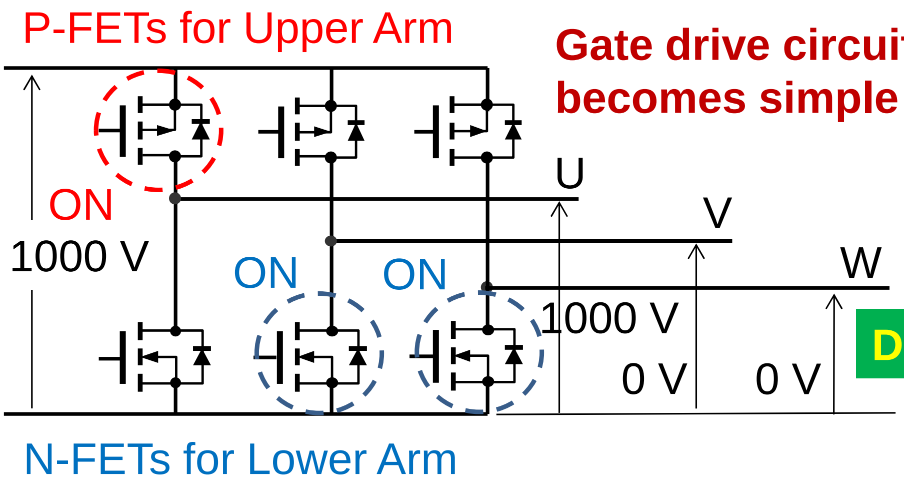
H. Kawarada et al.
Sci. Rep. 7 (2017)
42368.

[1] M. Noborio, T. Kimoto *et al.*, *IEEE Elec Dev Lett* **30 (8)** 831 (2009)
[2] S. L. Selvaraj, T. Egawa *et al.*, *IEEE Elec Dev Lett* **33 (10)** 1375 (2012)
[3] T. Nanjo, Y. Tokuda *et al.*, *IEEE Trans Elec Dev* **60 (3)** 1046 (2013)
[4] M. Wong, M. Higashiwaki, *et al.*, *IEEE Elec Dev Lett* **37(2)** 212 (2016)

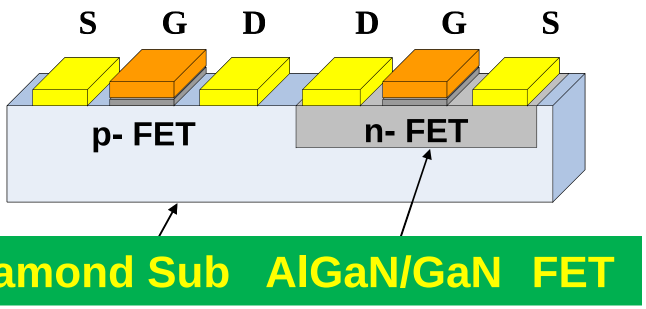
Advantage of p -channel FET in Power Complementary Circuit and System

“Diamond is Ideal Substrate” for Ideal Power System such as Complementary Inverter

1. Stage1: Diamond p-FET and AlGaN/GaN n- FET coexist or collaborate realistic solution

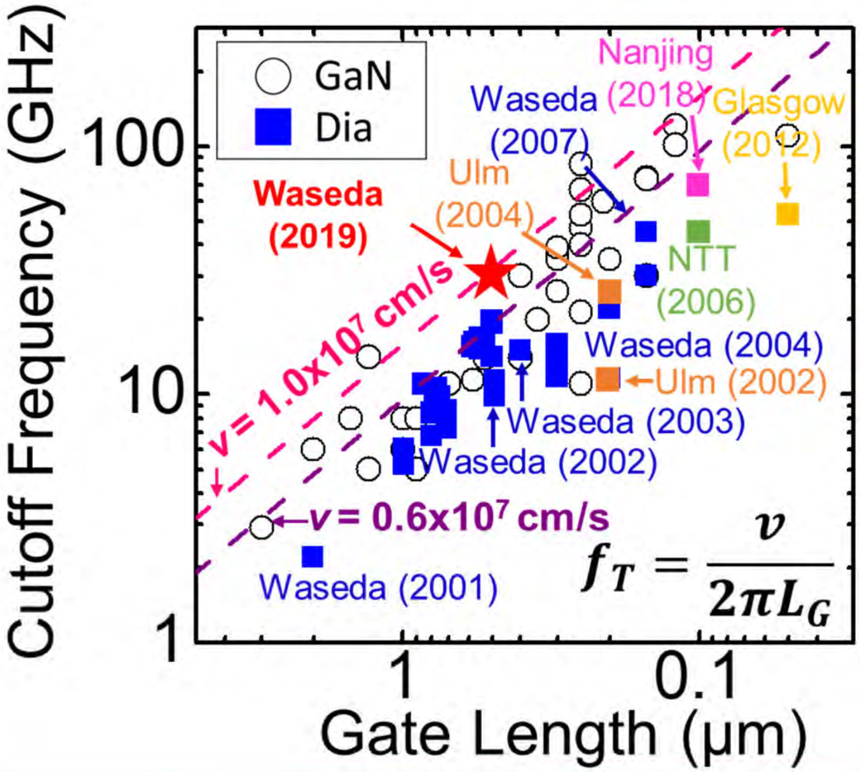


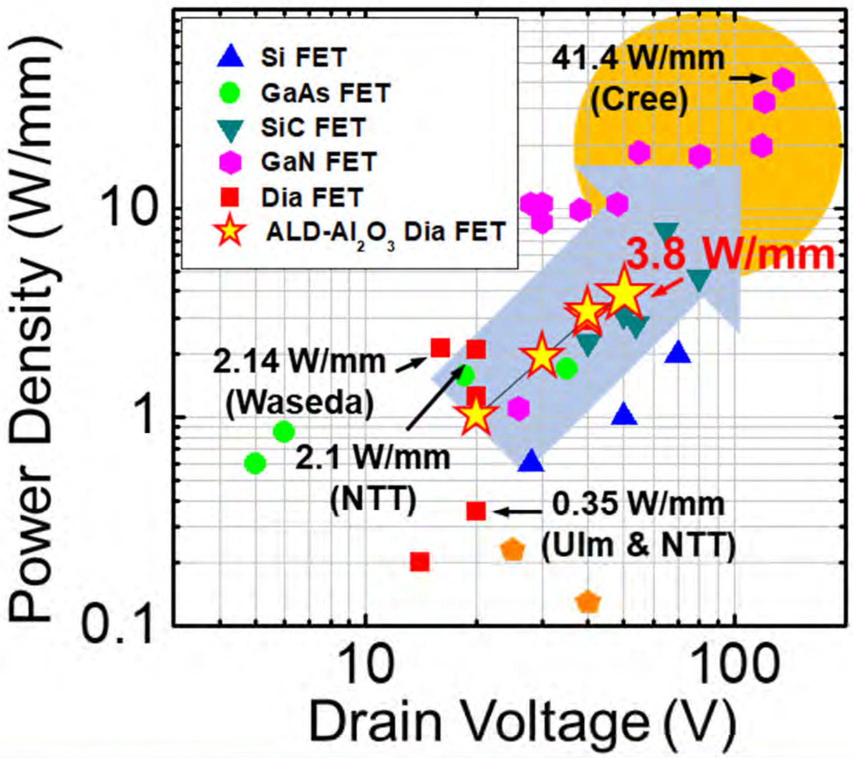
Gate drive circuit becomes simple



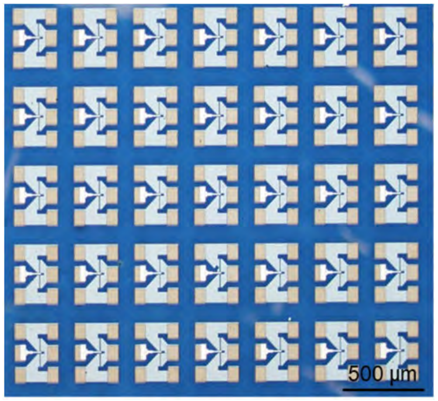
2. Stage2: Diamond n-FET and p-FET

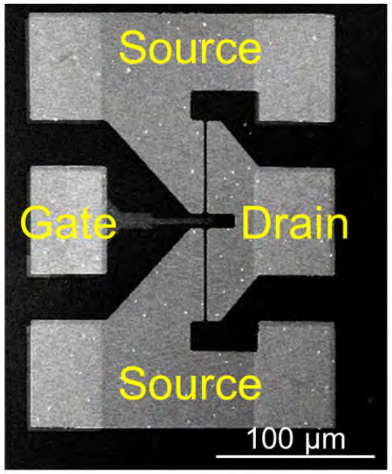
Overview of Diamond p-FET





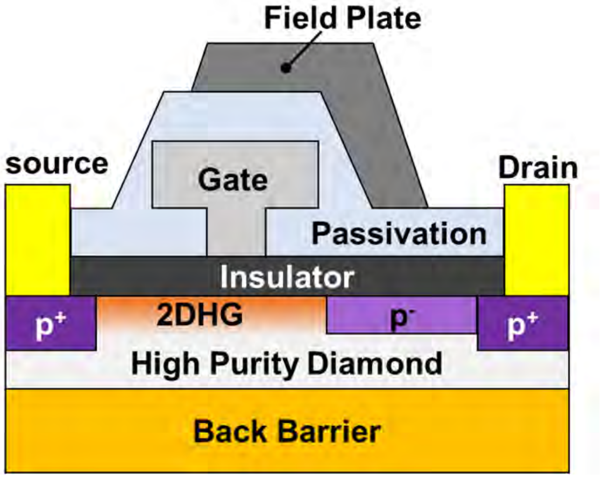
Diamond FET is a promising p-FET complementary to GaN n-FET



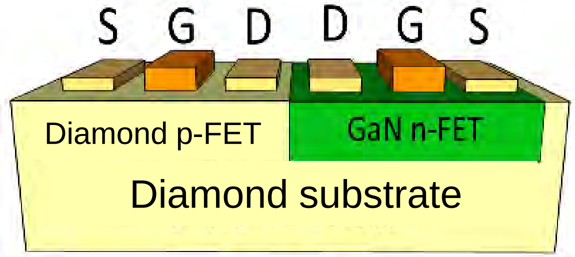


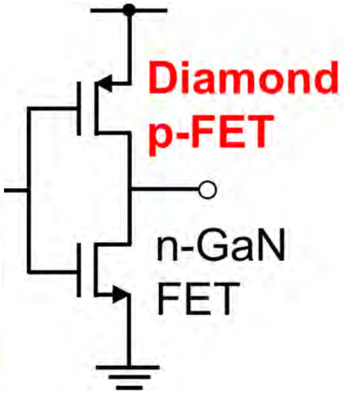
◆ Advanced RF Diamond p-FET

Aiming for further high frequency and high power diamond p-FET



◆ Complementary FET



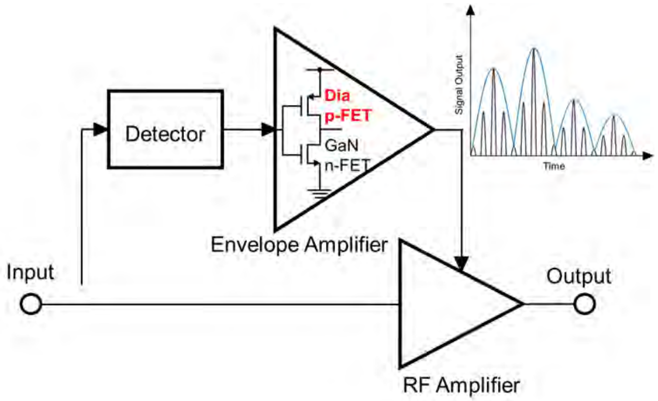


GaN can be heteroepitaxially grown on diamond →Diamond p-FET and GaN n-FET can be fabricated on one chip

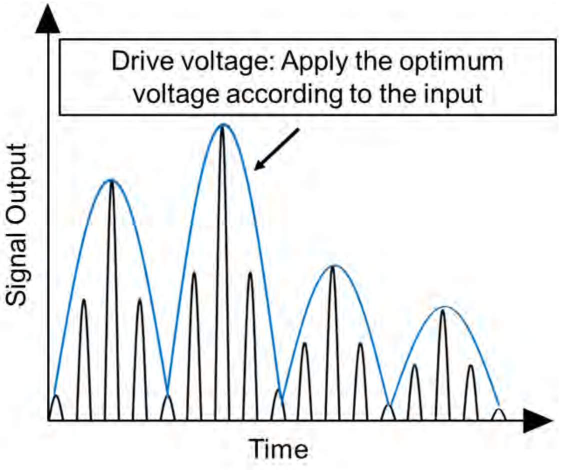
Advanced RF Diamond p-FET Proposal of Complementary FET

Application of Complementary FET for Base Station

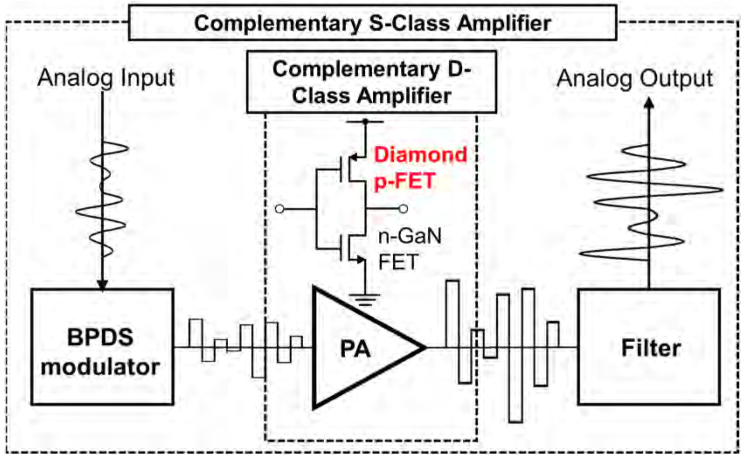
- Complementary Envelope Tracking Amplifier



- Complementary S-Class Amplifier



The efficiency of the back-off area
→Broadband and High Efficiency!



High efficiency of Class-S amplifier with 100 % ideal efficiency
Reduction of power consumption!

Summary

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INSTITUTE OF NANO OPTOELECTRONICS
RESEARCH AND TECHNOLOGY (INOR)

WASEDA University

- *GaN is now in the market and growing (getting attention in Malaysia 2021-2030)*

- *Diamond on the other hand, still needs time to mature (misconception of “price” still available)*

- *What can we expect in both GaN and diamond devices?*
  - *High frequency & High voltage Lateral MOSFETs*
  - *Vertical MOSFETs*

- *Complementary inverter GaN n-FETs and diamond p-FET is highly desirable (~10 to 20 years)*

- *If Malaysia can be one of the GaN and Diamond substrate material distributor, this will benefit our country’s economy for the next 2 decade.*

(natural gases/ghg gases/electricity are significantly cheap in Malaysia)

4th ISTEC 2020 INTERNATIONAL SCIENCES, TECHNOLOGY AND ENGINEERING CONFERENCE

Exploring Materials for Future

Thank You

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INSTITUTE OF NANO OPTOELECTRONICS RESEARCH AND TECHNOLOGY (INOR)

WASEDA University