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Wide band gap semiconductor technology: State-of-the-art

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ABSTRACT

Applications of the wide band gap (WBG) semiconductors, such as *GaN*, *AlGaN*, and *InGaN*, range from lighting and ultraviolet (UV) technology to high power, radiation hard, high temperature, terahertz (THz) and sub-THz electronics and pyroelectronics. Wurtzite (hexagonal) symmetry makes these materials to be quite different from conventional cubic semiconductors. Spontaneous and piezoelectric polarization associated with the wurtzite crystal structure induces two-dimensional electron gases at *AlGaN/GaN*, *AlInN/GaN*, and *AlGaN/InGaN* interfaces with sheet concentrations 10–20 times higher than those in *Si* CMOS. A high current carrying capability and a high breakdown field make these materials perfect for high power applications. Adjusting the energy gaps of $Al_xGa_{1-x}N$ and of $In_xGa_{1-x}N$ by varying the molar fraction changes the wavelength of light they emit or absorb and enables light and UV emitters, solar cells, and photodetectors operating from THz and infrared to deep UV range. Blue, green, and white LEDs using *InGaN* revolutionized smart solid-state lighting. *AlGaN* UV LEDs are used for water purification, fighting antibiotic resistant bacteria and viruses, and dramatically increasing produce storage time. *InN, ZnO,* and *BN* have potential to compete with the *AlN/GaN* family. Diamond has re-emerged not only as a substrate for a record heat removal but also as a viable THz detector material. The WBG technology has many difficult problems to solve. High dislocation density in the WBG materials leads to a low efficiency of deep *AlGaN* UV LEDs and reliability problems of high power devices. Non-uniformities of the electric field distribution cause a premature breakdown. Using ultrathin WBG quantum well layers and nanowires and exploring radically new physics-based device designs might alleviate or even solve these problems.

1. Introduction

Silicon technology is reaching its age of maturity. Ever since the 20 nm feature has been reached, the cost per Si transistor has been climbing with decreasing the feature size (see Fig. 1a) and silicon is expected to yield its dominant position in the power electronics area (see Fig. 1b). The next breakthrough in electronics and photonics will rely on new materials that include WBG semiconductors [1–20]. The existing and potential applications of the WBG devices go far beyond power electronics [21] and include blue, green, white light, and UV emitters [22–25], solid state lighting [26–28], water, food, air sterilization [29,30], detection of biological agents [31], dermatology [32], visible-blind photodetectors [33,34], high power switches [35] high power microwave switches [36,37], power sources for wireless communications, harsh environment and high temperature electronics [38,39], Surface Acoustic Waves [40–42] devices, acoustic-optoelectronics [43,44], pyroelectric sensors [45,46] and THz and sub-THz electronics [47–49]. Nitride [50,51], and SiC [52–54] materials and devices are already being commercialized, but diamond [55,56], ZnO [57], and even BN [58] might also find important applications. Diamond has been explored as a substrate for GaN transistors [59]. Applications of p-diamond for THz and sub-THz detection have been recently proposed [60].

One example of novel emerging wide band devices is Deep UV Light Emitting Diodes (DUV LEDs). These devices could find applications in fighting Health Care Associated Infections (HAI) [18]. It is estimated that HAI kill more people than the breast and prostate cancer combined. There is 5% chance of getting HAI for each hospital admission [61]. For seniors (people older than 65 years) the chances of getting an HAI are at least a factor of 3 larger (69% of HAI cases in US are MEDICARE of MEDICAID cases). Each year in U.S. hospitals there are an estimated 1.7 million HAI cases and approximately 100,000 deaths per year. A recent practice of using iPads to be signed by patients on the screens could make this problem even worse by spreading germs from a patient to a patient.

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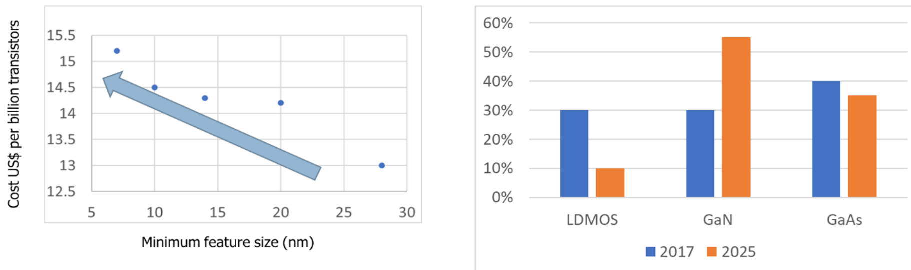


Fig. 1. Cost of Si transistor for different feature sizes (a) and market share of Si and compound semiconductors devices.

Fig. 2. Professor Sophia Lubensky (a) who died because of a hospital acquired infection and her famous Russian-English dictionary of idioms.

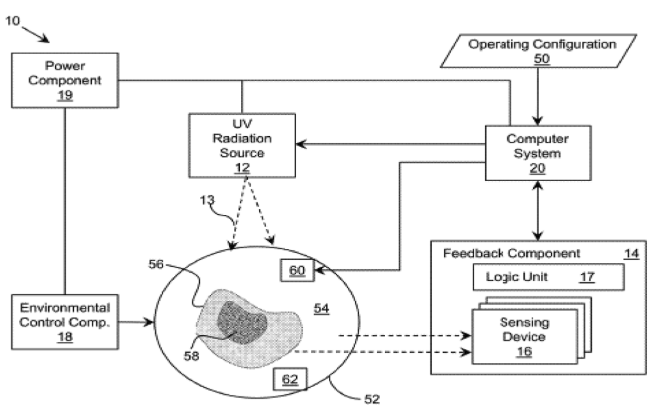


Fig. 3. Schematics of the disinfection system using DUV LEDs [29].

history, Professor Sophia Lubensky was killed by an HAI (see Fig. 2). Deep UV LEDs provide radiation killing germs [25]. Fig. 2 shows the schematics of the disinfection system using DUV LEDs.

Even a bigger challenge is to adjust to a tremendous poulation growth, primarily in the undeveloped world, with a commensurate increase in slum dwellers (see Fig. 5a), lack of clean water, and food shortages (see Fig. 5b). The DUV LED technology could contribute to the solutions of these problems by enabling local water purification systems [23,25,62] (see Fig. 6), improving crop yields [63] (see Fig. 7a), decreasing waste by increasing the food storage time [64], and improving the quality of produce (see Fig. 7b). Fortyeight hour exposure to UV light emitted by DUV-LEDs (282 nm peak wavelength) resulted in greater than two-fold increases in two different flavonoids, Cyanidin and Querce tin, in red leaf lettuce grown in simulated winter greenhouse conditions. Cyanidin is a red pigment found in many fruits and vegetables. Thus, treatment with the wavelength that is nearly

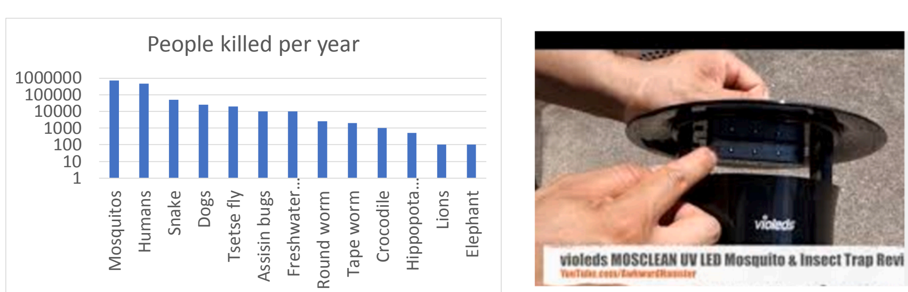
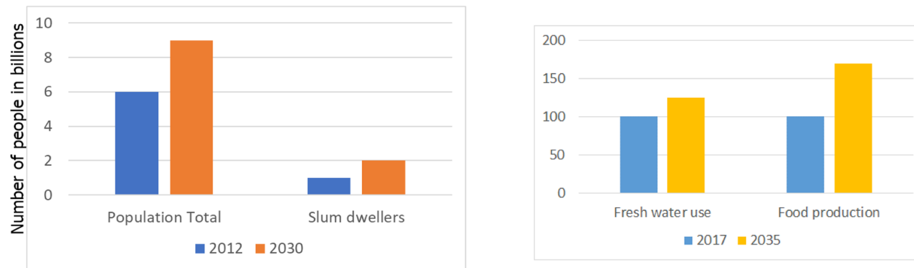


Fig. 4. People killed per year by different sources (a) and Deep UV LED Mosquito trap killing mosquitoes spreading the Zika virus.



(a) (b)

Fig. 5. Numbers of slum dwellers (a) and expected increase in water and food consumption (b).

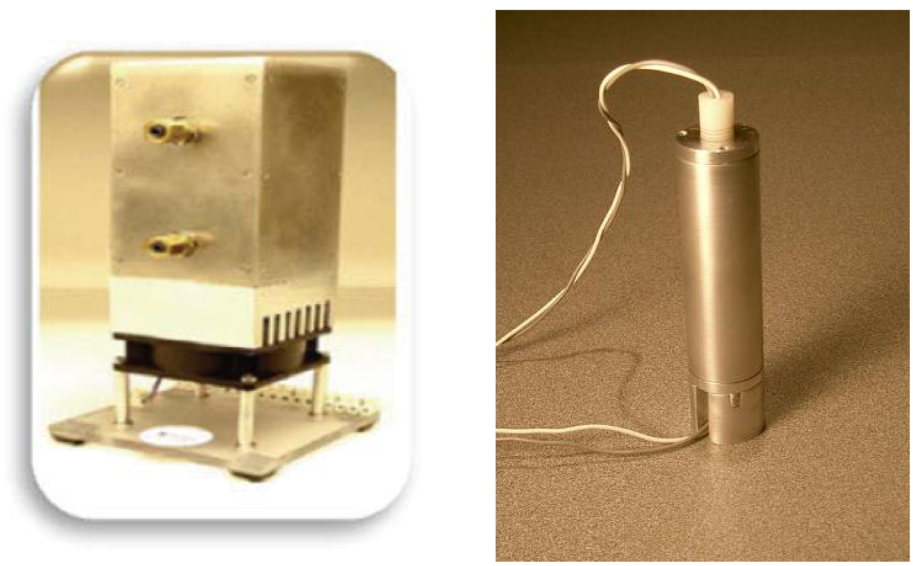
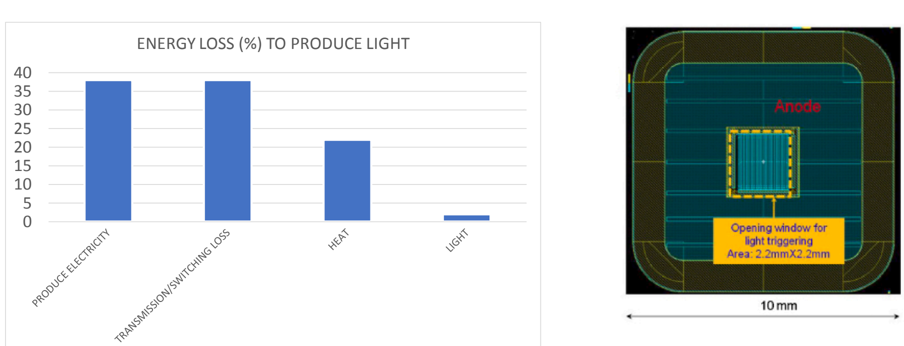


Fig. 6. Portable water purification systems [64].

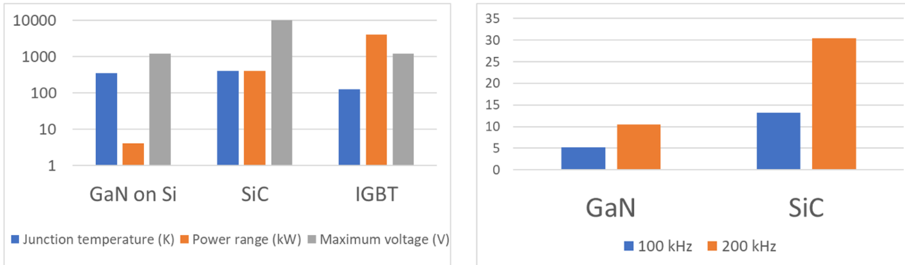
(a) (b)

Fig. 7. System for illumination crops by DUV LEDs (a) and comparison of red leave cabbage leaves not illuminated by DUV LEDs (sample A) and illuminated by DUV LEDs (samples B and C) 0 [63]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



(a) (b)

Fig. 8. Energy losses in producing light (a) and SiC 12 kV 1300 A thyristor for a more efficient switching at high voltages [67,68].



(a) (b)

Fig. 9. Comparison of Si IGBTs and GaN and SiC transistors (a) and GaN and SiC switches.

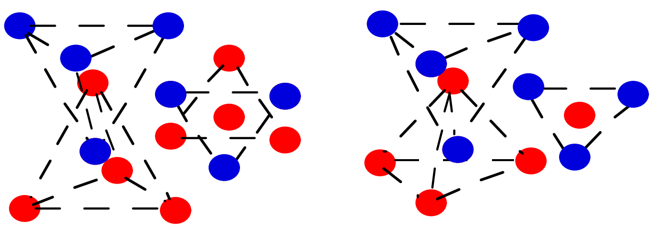


Fig. 10. Zinc blende and wurtzite crystal structures.

absent in sunlight dramatically enhanced both the concentration of nutritionally-important phytochemicals and the visual appearance of a widely-grown greenhouse crop [54]. Another big problem is diseases born by mosquitoes (see Fig. 4a) and DUV LEDs might help alleviate this problem as well (see Fig. 4b).

The wide band gap semiconductors could have a tremendous impact is high power electronics [65]. As seen from Fig. 8a, transmission/switching losses account for nearly 40% of the energy loss that could be reduced by using higher voltages for power transmission. This requires high voltage/high current devices, such as silicon carbide transistors (see Fig. 8b). Fig. 9a shows the predicted increase in the market shares for the wide band gap RF power devices. Fig. 9b compares the performance of GaN and SiC [66] power switches (See Fig. 3).

2. Material properties of wide band gap semiconductors

The key difference between many wide band gap materials, such as GaN or AlN, and silicon is symmetry. Most of the wide band gap materials have the wurtzite crystal structure (see Fig. 10), and, therefore, have pyroelectric properties. As was first pointed out in 1969, free carriers in pyroelectric materials screen the polarization. In ferroelectric-semiconductors, this effect leads to propagating domains of the electric field (see Fig. 11a). In AlGaN/GaN heterostructures, piezoelectric and spontaneous polarization changes attract free electrons or holes (depending on the crystal orientation) resulting in two-dimensional electron of hole gases (see Fig. 11b).

WBG semiconductors have strong bonds and high optical phonon energies enabling their superior materials properties for electronic and optoelectronic applications. The high mobility and high electron saturation velocity of GaN (see Fig. 12) and a high sheet carrier concentration (which about a factor of 10 higher than in silicon due to the polarization doping) support high current carrying capabilities and low on-resistances. A high breakdown field allows reaching large breakdown voltages. A large thermal conductivity (see Fig. 13) is important for handling high powers. Chemical inertness of GaN and diamond is important for device stability and biomedical applications.

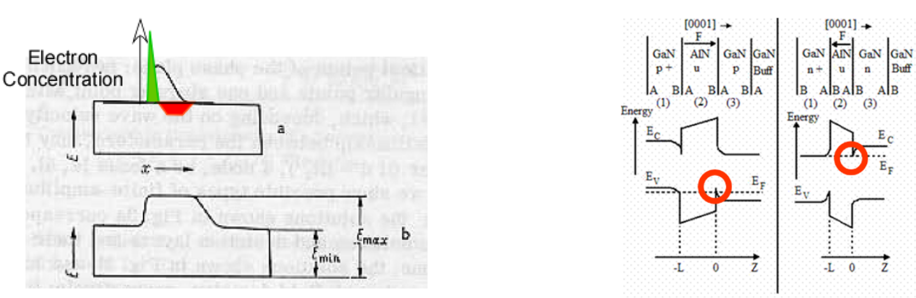
Table 1 compares the key materials properties of Si, SiC, and GaN. The superior material properties of wide band gap materials result in the large figures of merit compared to Si. Fig. 14 shows the combined figures of merit for Si, GaN, and SiC given by [72]

$$CFOM = \frac{\chi\varepsilon\mu v_s E_B^2}{(\chi\varepsilon\mu v_s E_B^2)_{Si}} \quad (1)$$

Here χ is the thermal conductivity. E_B is the breakdown field, $\mu$is the low field mobility, v_s is saturation velocity, and ε is the dielectric constant.

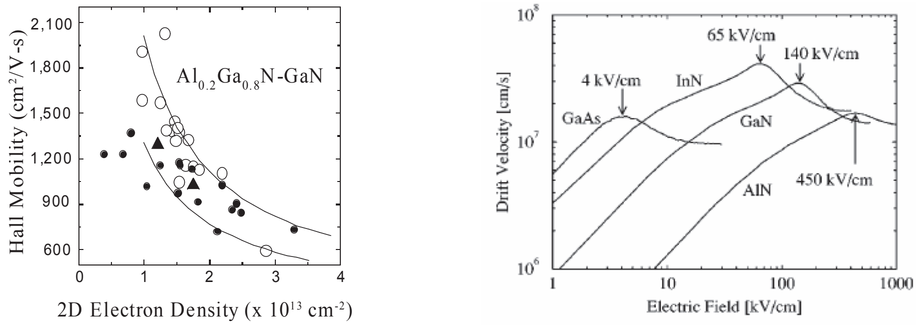
Fig. 14(a) shows the combined figure of merit. Fig. 14(b) shows the combined figure of merit, where the thermal conductivity is substituted with the values corresponding to the substrate, since both simulation and measurements show that the substrate thermal conductivity plays a dominant role in determining the overall thermal impedance (see Fig. 15).

Fig. 16 illustrates the pyroelectric and piezoelectric properties of III-N semiconductors enabling their application in sensing.



(a) (b)

Fig. 11. Filed distribution in ferroelectric semiconductors due to polarization screening (After [69]) (a) and band diagrams of AlN/GaN heterostructures predicting polarization doping [70]. (b). Red circles show the formation of two-dimensional hole and electron gases (depending on the crystal growth orientation). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



(a) (b)

Fig. 12. Two-dimensional electron density [71] (a) and electron drift velocity in nitride semiconductors (after [50]) (b).

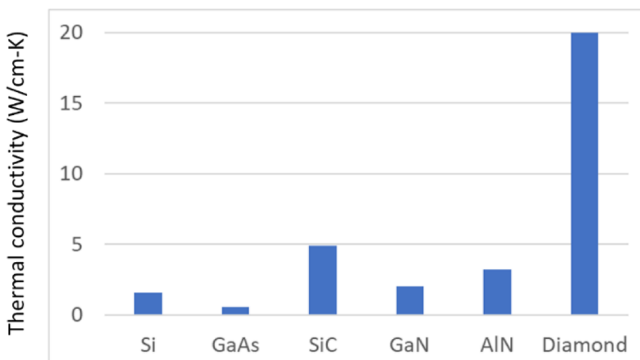


Fig. 13. Thermal conductivity of different semiconductors.

3. Wide band gap semiconductor technology

The epitaxial growth technology, Metal Organic Chemical Vapor Deposition (MOCVD) is the key technology determining the materials quality and, therefore, device performance and reliability. Fig. 17 shows the advantages of Migration Enhanced MOCVD (MEMOCVD™ that allowed us to decrease the dislocation density by over an order of magnitude. The MEMOCVD™ technology also enabled growing precise heterostructures and AlGaN/GaN percolated structures that allowed to implement transparent p-type contacts for deep UV LEDs (see Fig. 18).

Further advances in III-N power electronic technology will use novel device designs that account for the device physics of the nitride materials. Fig. 19 illustrates the advantages of the quantum well design of the channel of a AlGaN/GaN High Electron Mobility Transistor (HEMT). In addition to preventing or limiting parasitic space charge injection [75], an increased penetration of high energy electrons into the cladding layers should result in an increased breakdown voltage [76].

Using lattice matched AlInN/GaN structures [77] could provide additional advantages of higher current carrying capabilities, higher breakdown voltage, and higher operating temperature (see Figs. 20 and 21).

An important improvement in the GaN transistors design is the MOSHFET approach (see Fig. 22). In this design, the dielectric layer is separated from the active channel interface but still suppresses the gate leakage current (see Fig. 23).

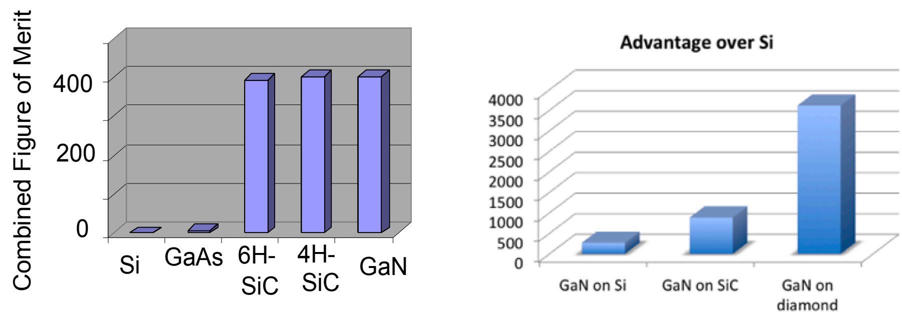
As was first shown in [84], the breakdown voltage of the GaN-based HEMTs is roughly proportional to the gate-to-drain separation (see Fig. 24a). A dramatic performance improvement could therefore be achieved by controlling the properties of the transistor surface between the gate and drain by introducing a Low Conducting layer (LCL) (see Fig. 24b). The LCL design (see Fig. 25) has allowed to improve performance of the RF switches and control the GaN HEMT breakdown voltages. Another way to control and improve the properties of this gate-to-drain region in the GaN power HEMTs and MOSHFETs is to use the perforated channel design (see Fig. 26) [85]. All these novel approaches could be combined to achieve superior performance.

4. Conclusions

Silicon technology is reaching its maturation level, and WBG semiconductors s compete with silicon in the areas of RF power electronics, power electronics, sub-THz and THz electronics and sensing. They enable photonic applications ranging from solid state lighting to emitting deep UV radiation. A different (non-cubic) symmetry and commensurate spontaneous and piezoelectric polarizations make the

Table 1
Key materials properties of Si, SiC, and GaN.

Material	Si	GaAs	6H-SiC	4H-SiC	GaN	AlN	Diamond
Bandgap (eV)	1.12	1.42	2.86	3.2	3.4	6.1	5.47
Breakdown field (V/cm)	10^5	10^5	10^6	10^6	10^6	5 10^6	7 10^6
Mobility (cm^2/Vs)	800	5000	350	650	> 2000 in 2DEG)	300	2000 (electrons) 2000 (holes)
Sat. velocity (10^7 cm/s)	1	1.8	2	2	2.5	2.5	2.5
Thermal conductivity (W/Kcm)	1.3	0.5	2.9	2.9	1.2	2.85	20



(a) (b)

Fig. 14. Combined figure of merit for different semiconductors (a) and for GaN on different substrates (b) [72].

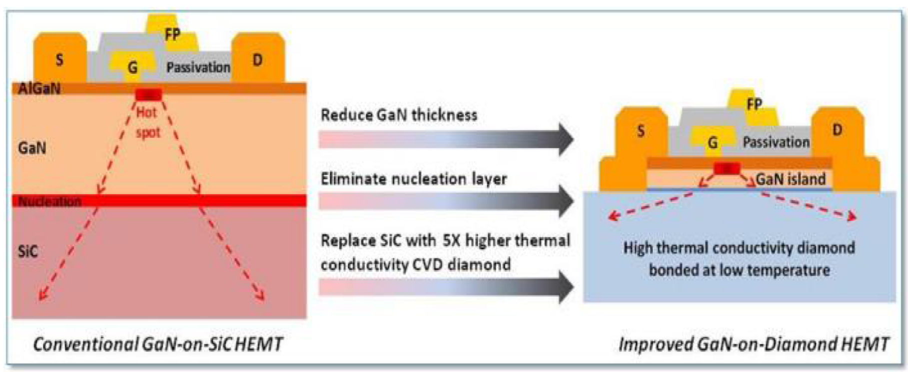
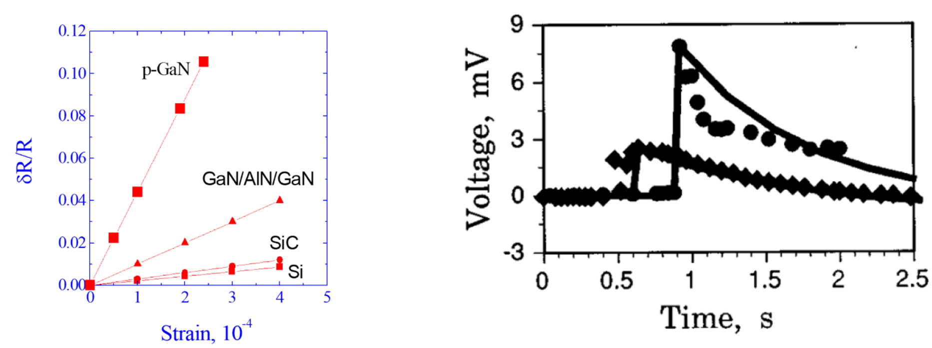
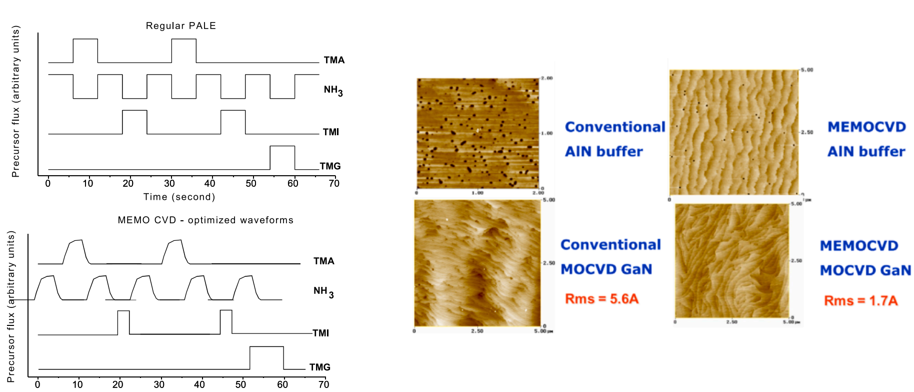


Fig. 15. Device-transfer GaN-on-diamond device approach. The hot spot of the GaN device is within 1 m of the diamond substrate and the device thermal resistance is reduced [59]. ©IEEE 2015.



(a) (b)

Fig. 16. GaN/AlN piezoelectric [73] (a) and pyroelectric (b) sensors [74].



(a) (b)

Fig. 17. MEMOCVD and MOCVD comparison [78].

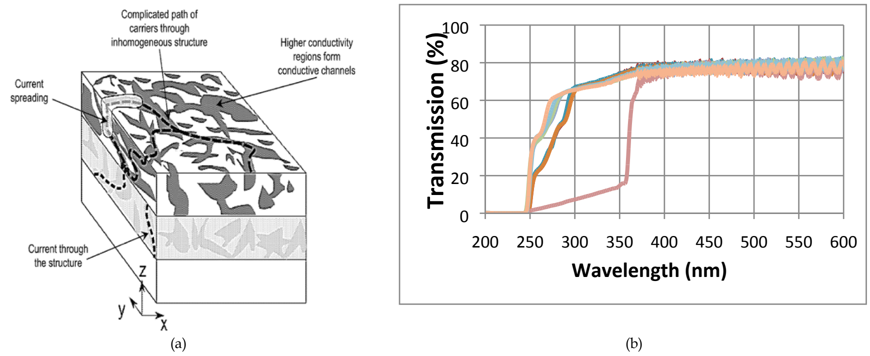


Fig. 18. Schematic of MEMOCVD grown transparent p-contact to deep UV LED (a) and improved contact transmission (b) [79,80].

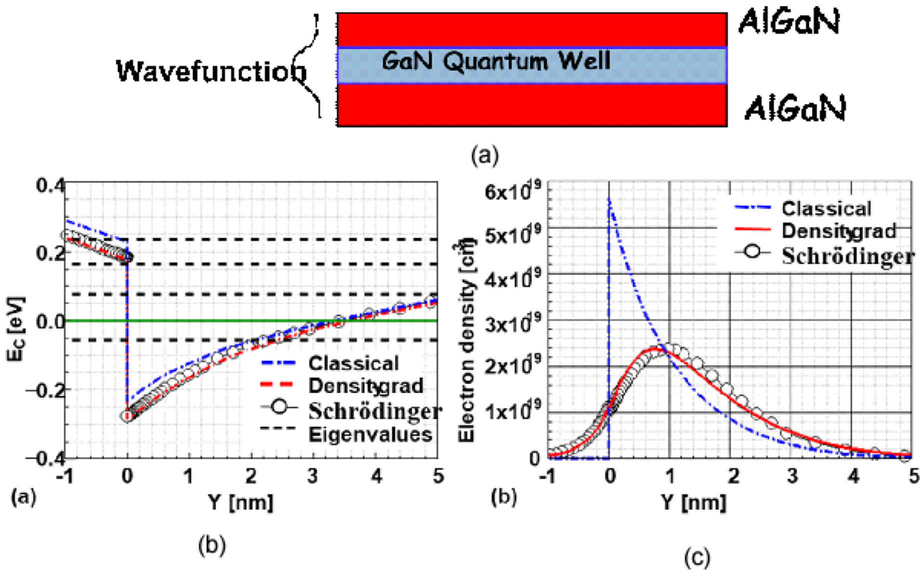


Fig. 19. AlGaN/GaN/AlGaN quantum well structure (a), band diagram (b) and wave function penetration into the barrier layer (c) [81].

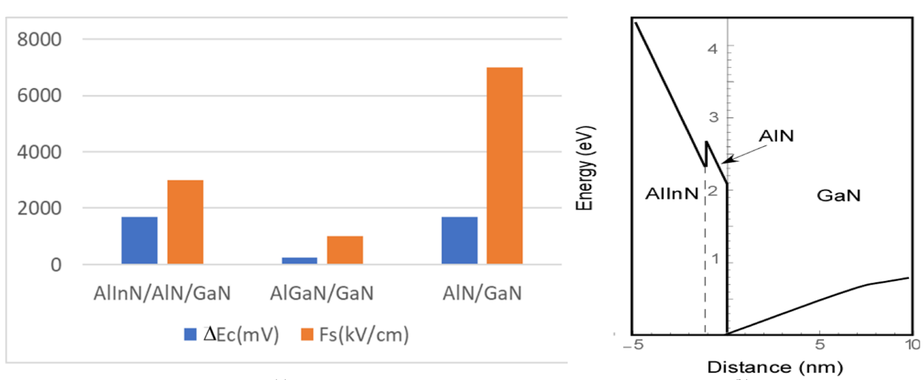


Fig. 20. Comparison of AlInN/AlN/GaN and AlGaN/GaN heterostructures: conduction band discontinuity (a) and the band diagram (b).

physics of the wide band gap semiconductor devices very different from that for more conventional cubic semiconductors. The superb materials properties of wide band gap semiconductors have promise of enabling orders of magnitude better performance than has already been achieved. Realizing this dream requires a deeper understanding of the device physics and physics based new approaches to materials and device technology.

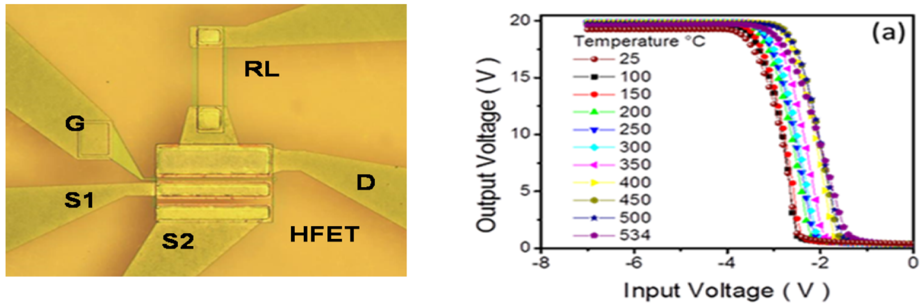
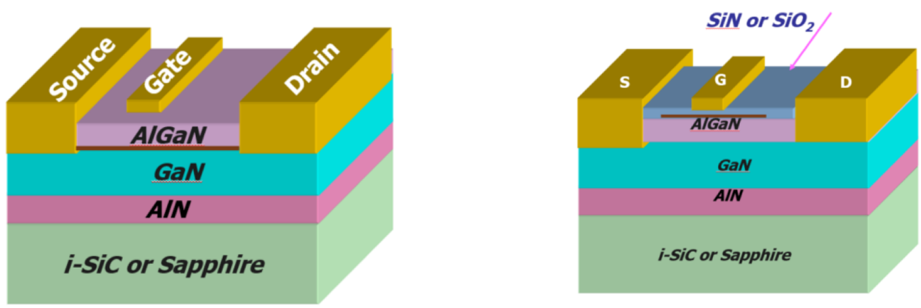
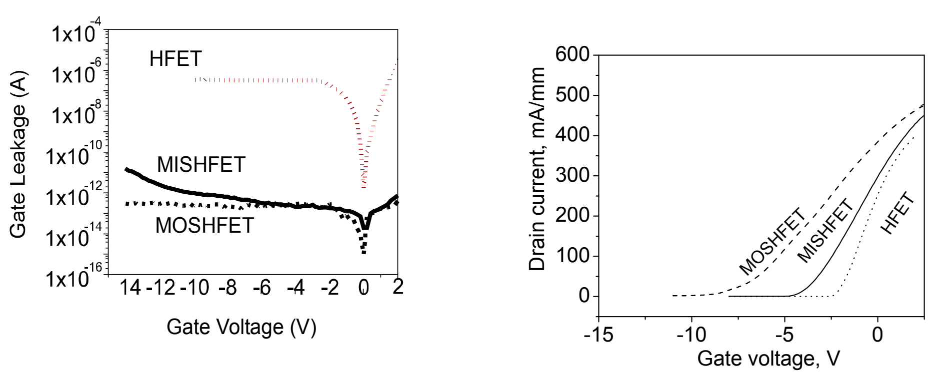


Fig. 21. High-T (500°C) AlInN/GaN Inverter IC optical image (a) and output-input voltage characteristics [82].



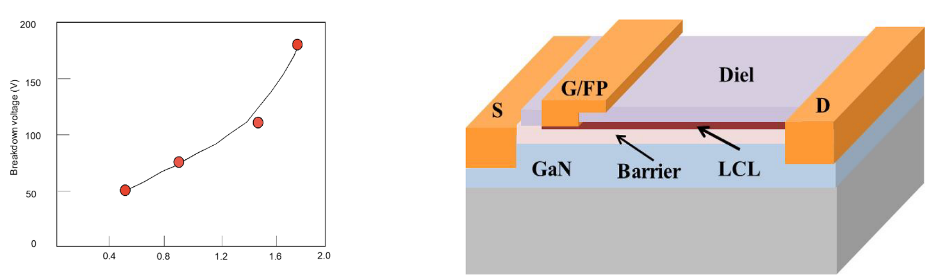
(a) (b)

Fig. 22. Conventional AlGaN/GaN HEMT (a) and AlGaN/GaN MOSHFET (b) [83]. © IEEE 2003.



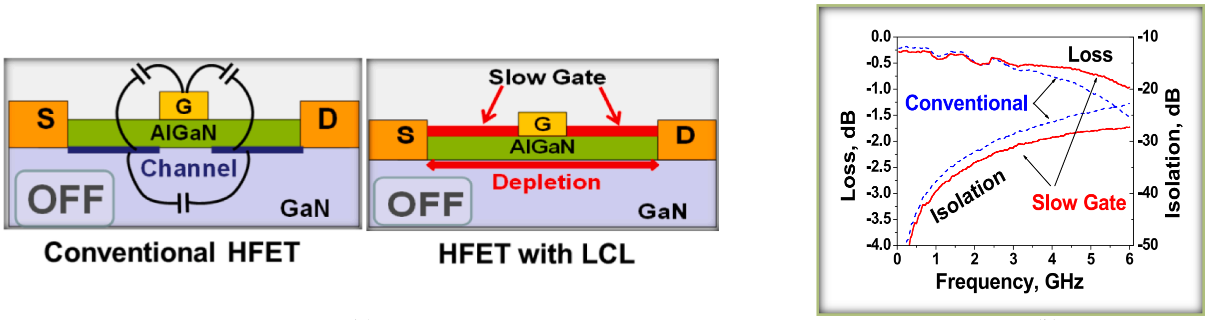
(a) (b)

Fig. 23. Leakage current (a) and transfer characteristics of AlGaN/GaN HFET, MOSHFET, and MISHFET [83]. © IEEE 2003.



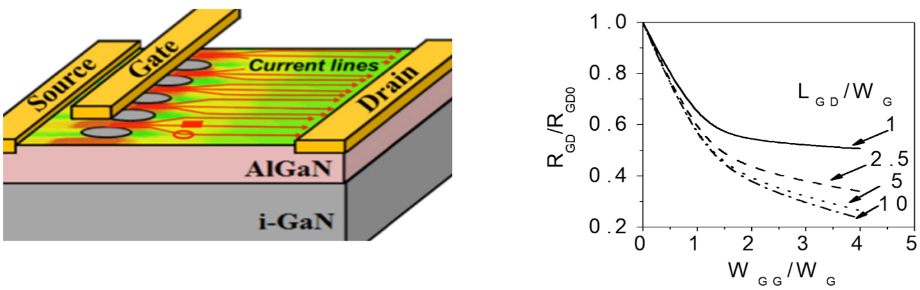
(a) (b)

Fig. 24. Breakdown voltage as a function of the gate-to-drain spacing [75] and AlGaN/GaN HFET with LCL (after [86]).



(a) (b)

Fig. 25. Reduction of HFET OFF-state capacitance using "slow" LCL gate (a) and resulting improvement in the RF AlGaN/GaN RF switch performance [86].



(a) (b)

Fig. 26. Simulated current density distribution in perforated gate AlGaN/GaN HFET (a) – The current density through the gate island decreases by half 1 um closer to the drain – And reduction of the On-resistance in PC-HFET in comparison with conventional HFET with the same gate width (b). W_{GG} is the gap between the channel openings, W_G is the gate island width, L_{GD} is the gate-to-drain distance [87].

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