Power Electronic Devices in the Future

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***Abstract*— This paper discusses extrapolations of current silicon power device technology into the future, followed by discussions of wide band gap (WBG) power devices with a focus on silicon carbide and gallium nitride. Other WBG materials are included from carbon, such as diamond and nanotubes, to various nitrides. Far future material development, that may impact power electronic devices decades out, is also discussed.**

***Index Terms*— Carbon nanotubes, diamond, gallium nitride (GaN), power semiconductor devices, silicon carbide (SiC), wide band gap semiconductors.**

I. Introduction

WHAT is the future of power electronic devices? This paper covers a few well documented, near-term trends for power semiconductor devices. Discussion is then devoted primarily to longer-term emerging trends; however, these are advances still based on extrapolations of present-day technology. The more interesting part are some outlandish thoughts, not intended to be all inclusive, on the distant future in power processing devices and the potential attributes of these future components.

Of the fundamental forces in this universe, electromagnetism is the one that seems to be the best compromise of force magnitude, relative size of associated materials (compared with humans), and relative ease of use for information and power applications. Hence, photons and electrons, the medium by which electromagnetism is used, implies that electronics will continue as the appropriate type of engineered system far into the future. The long-term unknowns really revolve around how energy (and information) dense these systems can be made, what materials will be used, and how other machines and humans will interface with them.

II. Material Abundance

A. Silicon

Silicon (Si) will not be discontinued or replaced anytime soon. The better question is, to what degree will Si be replaced by other materials? Si is too ubiquitous (see Fig. 1) in the Earth's crust, as well as in the universe generally, too useful in many applications, and its use in technology represents too large a part of the world's gross domestic product. Therefore, it will remain a staple of the electronics industry for many decades. Si should be considered a staple material for personal and industrial use just as paper continues to be widely used even though electronic storage of information continues to try to replace it. It is not at all clear that electronic storage of information will prove better than paper in the long term, so why assume that Si will not continue to have a role in power electronics far into the future?

Manuscript received April 8, 2013; accepted April 22, 2013. Date of publication April 26, 2013; date of current version July 3, 2013. Recommended for publication by Associate Editor Don F. D. Tan.

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Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JESTPE.2013.2260594

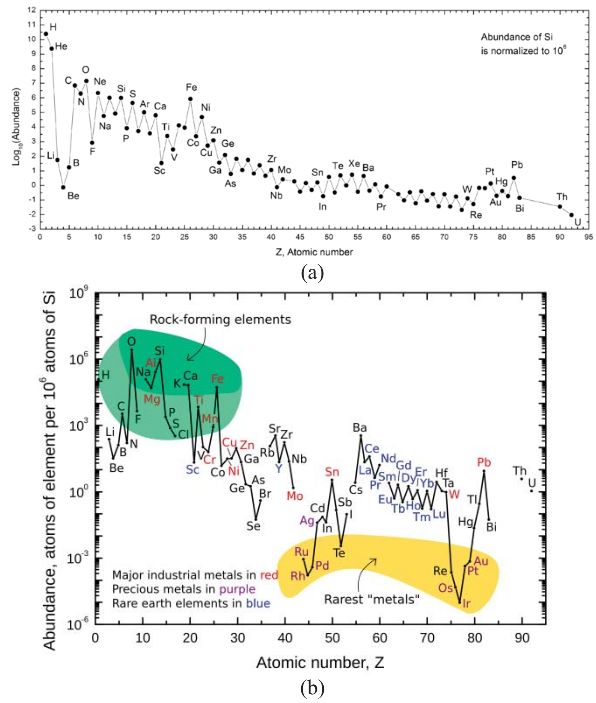

Fig. 1. (a) Estimated abundance of chemical elements in the solar system and (b) in Earth's crust (data from [1]). (a) User: Example/Wikipedia Commons/CC-BY-SA-3.0. (b) Gordon B. Haxel, Sara Boore, and Susan Mayfield/Public Domain.

B. Alternative Materials

As far as alternative materials, carbon (C) is 3.5 times more abundant than Si, thus suggesting silicon carbide SiC or C devices (along with Si devices) could easily be produced far into the future, based on raw material availability terrestrially and extraterrestrially (if and when humans or machines take up residence elsewhere in the universe).

Hydrogen and helium are the most abundant elements in nature, created at the time of the origination of the universe.

Lithium, beryllium, and boron (the next three elements in atomic number) are not synthesized in significant quantity during the initial creation of the universe and are not produced inside of stars. Small (on the scale of the solar system or the universe) amounts of these elements are created by the cosmic ray impact of heavier elements. It is interesting to note, however, that lithium is relatively abundant in the Earth's crust [see Fig. 1(b)].

Carbon, the fourth-most abundant element, is readily made in nucleosynthesis in stars. A general trend in stellar element creation is that even atomic numbered elements are more stable then odd atomic numbered elements and hence exist in more abundance.

Iron (Fe) is the most stable element that is produced in many stars. Elements heavier than iron are made through energy absorbing processes in very large stars and are less abundant as their atomic number increases.

III. Near-Term Trends

A. Improved Material Quality/Interfaces

Future improvements in Si devices [e.g., metal–oxide–semiconductor field-effect transistors (MOSFETs)], insulated-gate bipolar transistors (IGBTs), and thyristors) will start with improved material quality and improved interfaces to eliminate unwanted interface states (e.g., oxide semiconductor interface). Material defects are a root cause of device failures, with these defects and corresponding secondary effects exacerbated by additional energy from high electric fields, large current densities, increased temperature, and the interface stress of material layers.

Power cycles endured during the operation of power electronic drives affect the lifetime and ultimate reliability of devices and their packages. For example, the power electronic devices in a drive for an urban tram may experience up to 10^8 power cycles with an associated device temperature (Si junction temperature) excursion of over 80 °C [2], [3]. The failure rate [failure in time (FIT), where 1 FIT = 1×10^{-9} failures per device-hour] in IGBT devices has decreased from 1000 FIT in 1995 to the present rate of a few FIT [4]. The FIT of the gate driver and associated electronics is now higher than the IGBT device. IGBT package and device-related failures account for $\sim$35% of the faults in power electronic drives.

Future power handling capability will be directly tied to how well these material quality issues are resolved.

B. Adaption to Specific Converter Topologies

Another trend that offers great potential is the adaptation of device performance to specific converter topologies. A combined understanding of device and circuit design and of the behavior of the devices in these circuits often permits major cost reductions when safe operating area (SOA) limits are well understood. In this sense, the use of soft-switching converters in medium-voltage applications offers great potential when the power devices are designed and specified for this type of operation.

C. Reduction in Chip Thickness

One general trend noted for thyristors, MOSFETs, and IGBTs is the reduction in chip thickness. An example is the drop in thickness from 220 to 100 μm for a 1200 V IGBT between 1990 and 2005 [9]. This push to use minimal material will continue as handling and fabrication technology improves and thermal performance is maximized, allowing controllable operation near maximum junction temperatures for a particular device type and material (e.g., 200 °C or higher for Si [10]). The improvement threshold in IGBT current-handling capability is also thought to be several times higher than today's devices at lower forward voltage [11].

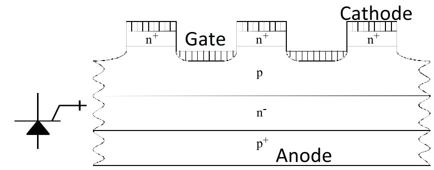

Fig. 2. Cross section of SGCT cells (n^- base is not to scale).

D. Controlling Material Type

Another broad trend is the improving ability to control material type, (including doping impurities) and geometry within larger device structures for full (3-D) fabrication and functionality. Three current examples of this trend are superjunction MOSFETs, buffer layers or field-stop layers in IGBTs and thyristors, and position-dependent carrier lifetime control [e.g., symmetric gate commutated turn-off (SGCT) devices].

Superjunctions (SJs), also called charge compensation structures, flatten the electric field profile in the base region of a device, thus allowing for thinner regions to achieve the same voltage rating. A thinner base region improves the switching frequency and conduction losses. SJ designs are utilized in power MOSFETs and are being investigated for bipolar devices, such as transistors. Further extension to thyristors is anticipated in the future [12].

An SGCT is developed and commercialized for many years [13], [14]. For example, SGCT devices rated for 6.5 kV are incorporated into medium-voltage current-source drives by several companies, providing better performance with fewer semiconductor devices (IGBT multilevel inverter design).

The SGCT device (shown in Fig. 2) has no anode shorts and no n^+-buffer layer between the n^--base and p^+-anode [common in gate turn-off thyristor (GTO), making it a nonpunch-through structure]. Further performance improvements are made by using two energies of protons to irradiate the device during processing to create two distinct low carrier-recombination lifetime regions: one near the upper p-base/n^--base junction and the second region near the n^--base/p^+-anode junction. The localized lifetime control lowers the turn-off energy losses and the associated anode turn-off tail current and provides improvements in other parameters.

The continued use and further adoption of GTO-type devices will depend upon the value gained from integrating gate drives into modules, such as in the integrated gate controlled thyristors IGCT. Already there is a trend to replace GTO devices with high-powered IGBTs, particularly in voltage source converters.

E. Improvements in Nanotechnology

The continuing improvement in nanotechnology, particularly using lasers to excite precise chemical bonding, will usher in a new era in fully controllable 3-D design [15]. This will create devices unimagined today for power switches, such as shown in Fig. 3. Future device geometry and material

Fig. 3. Conceptual rendering of variable diameter CNTs grown by laser-assisted deposition (by Joel Brehm).

layers/structure processing will be fully automated and controllable, in robotic fabrication, where devices can be designed from a computer interface.

F. Other Trends

Another characteristic desired for future devices is fully controllable (on-state and off-state) bidirectional switches. This means that the devices can be externally commanded to conduct current or withstand voltage in either direction/polarity, all in one switch structure. Because of the nature of material interfaces, optimized devices may have metal-semiconductor portions (Schottky barriers), semiconductor-insulator interfaces (e.g., oxides), and impurity-doped regions all integrated together. Clearly the present IGBT and GTO technologies already meld various interfaces together for improved characteristics. Another such device currently available is the merged pin-Schottky junction (MPS) SiC diode, as shown in Fig. 4.

The merging of bipolar and unipolar operation (device structures) and voltage gating for control is a design trend that seems likely to continue for optimum and enhanced performance. Some of these hybridized structures are currently created with mixtures of discrete components [16], but should eventually be integrated into a monolithic supercrystal.

IV. Long-Term Trends

A. Total Integration and Control

Future control signals and gating (firing and turn-off) signals may evolve to be photonic in nature instead of electronic. Light-source digital coding can provide secure communication with power converter switches and have very high noise immunity. Only the very last stage of the control system needs to convert photons to electrons and holes for electronic injection of the appropriate signal; or, in many cases, direct light injection into the power switch may suffice.

IGBT modules were also developed that integrate the usual IGBT device and clamp diode with a drive integrated circuit that can include sensing and protection functions [17]. These intelligent power modules are typically used for low power converters, but their introduction into high power converters is expected to occur in the future. Finally, more functionality with respect to control, gate drive, current and voltage sensing, and overload limiting functions continues to be integrated into power device modules or onto the silicon itself as new methods for managing complexity are developed. This general trend of increased power capability for IGBTs and more functionality should continue into the foreseeable future.

The current smorgasbord of layers and materials used in device packaging is a testament to the difficulty in meeting competing demands for safety, electrical isolation, and thermal transparency. It is a marvel that devices and modules perform as well as they do. Future improvements will trend toward moving components like IGBTs further into press packs, similar to high-voltage diodes and thyristors. Press packs have upper and lower copper pole pieces that connect (with a dry contact) directly to the IGBT collector and emitter [18]–[20]. Often a molybdenum or tungsten spacer is inserted between the upper pole piece and the IGBT for a better match of the materials with respect to the coefficient of thermal expansion (CTE). The press pack eliminates solder joints and wire bonds and has demonstrated improved reliability over typical modules under accelerated life tests, including vibration, shock, and thermal cycling [21]. The failure mode of a device in a well-designed press pack is a short circuit that is desirable in a large series configuration of devices in a high voltage application. Standard modules with wire bonds can have several failure modes that usually end up appearing as an open circuit. An open circuit condition is desirable only in parallel connected device applications [22].

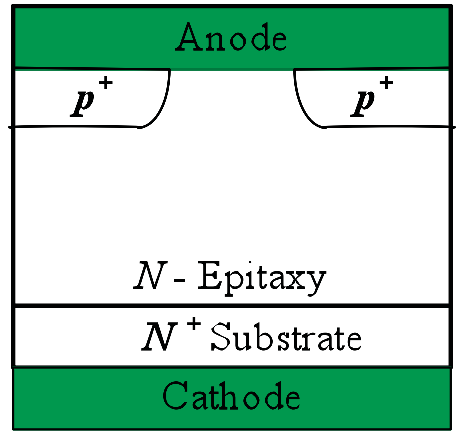

Fig. 4. MPS rectifier (SiC).

The SOA of small area (IGCTs) exceeds 1 MW/cm^2, while large area IGCTs have a reduced SOA around 200–300 kW/cm^2 [23]. This limit is determined to a great extent by the maximum controllable turn-off current and is greatly influenced by the stray inductance in the gate turn-off driver circuit. Integrating the turn-off circuit into the package of the gate commutated thyristor (GCT) wafer would allow for a much higher SOA. This integrated commutated thyristor concept, see Fig. 5, is a promising innovation for the next generation of high-power devices [24], [25].

Other advanced thyristor concepts are discussed in [16].

B. Current Contenders—SiC and GaN

Much has been presented on the benefits and shortcomings of the two semiconductor materials touted as the next-generation for power electronic devices: SiC and gallium nitride GaN. A continuation of devices designed in SiC, based on current Si structures, is happening for the near term at least. This includes recognizable devices, such as diodes, MOSFETs, IGBTs, and thyristors. Other power device structures not typically produced in Si but being explored in SiC, include power BJTs and power junction field effect transistors (JFETs).

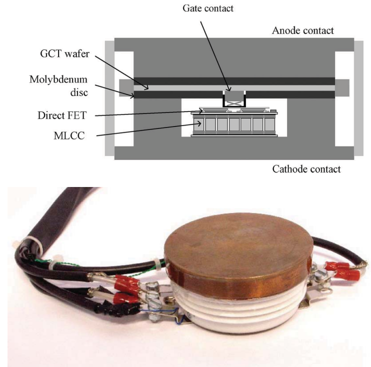

Fig. 5. Integrated gate turn-off circuit with GCT wafer combined into one package.

There is a ten-fold improvement in SiC MOSFET voltage ratings from sub-kV breakdown to over 10-kV breakdown between 1997 and 2008 [26]–[43]. Power JFETs, IGBTs, and thyristors fabricated in SiC have trended similarly with respect to breakdown voltage rating while optimizing specific on-resistance and current density capability over the past ten years [44]–[58]. These incremental device performance improvements will continue as application demands ultimately determine that device type, device designs, and ratings regimes are successful in the marketplace.

Micropipes in SiC are nearly eliminated (now <2.5 per cm^2). Other defects are likely to be resolved within several years. These include threading screw dislocation (TSD) (TSD density is currently $\sim 1000\ cm^{-2}$) [5], basal plane dislocation (BPD) (BPD density is currently a few to 10 s cm^{-2}) [6], threading edge dislocation (TED) (TED density is presently 100 to 1000 s of cm^{-2}) [7]. Comparatively, (GaN) can have bulk defect densities exceeding $10^6\ cm^{-2}$. Currently, several manufacturers have produced SiC diodes that have a FIT of <0.5 [8]. However, all non-Si devices are conduction-current limited in their ratings because of material quality.

The capabilities of GaN junction and MPS diodes are continuing to develop. High electron mobility transistor (HEMT) structures are the major device family being explored in GaN at present (see Fig. 6). One of the major advantages of GaN HEMTs over SiC is the potentially low cost to grow a thin GaN epilayer on a relatively inexpensive Si substrate.

A current problem with these structures includes the need for normally off operation. The lattice mismatch between the AlN buffer layer, GaN, and substrate material (Si, SiC, or sapphire) introduces defects and thus limits operational characteristics and lowers reliability. However, GaN substrates are becoming available and should greatly reduce interface states detrimental to device performance in the near future. Current degradation (collapse) because of electron trap sites created by surface defects and dislocations is being addressed as progress is made on material quality. SiN passivation is also used to help mitigate some of these effects. Another major disadvantage is that the GaN HEMT device lacks any avalanche capability. There is no *pn*-junction to absorb the avalanche energy. When a GaN HEMT breaks down from a too high applied voltage, it usually punctures through some dielectric layer that is an irreversible process. This presents a great challenge for the power electronics community. Further adoption of the GaN HEMT may hasten increased use of soft-switching topologies to reduce the avalanche energy requirement on the switching devices.

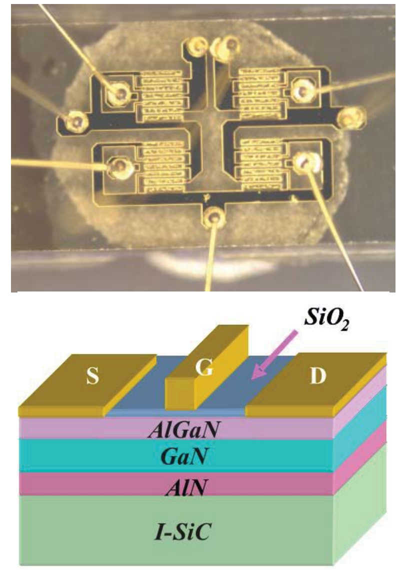

Fig. 6. GaN transistor in typical lateral design. Current flows in GaN layer near AlGaN interface.

Lateral device structures are field limited; but by incorporating field plates, improvements in breakdown capability are being achieved [59]. Vertical structures [60], [61] as well as normally off designs, are proposed and are under development [62].

C. Diamond

By far, one of the best materials for future power devices is C (diamond), partly because of its enormous bandgap, which is 73% larger than SiC (4H). It has one of the highest thermal conductivity values (a factor of four to five times higher than SiC) and electron and hole mobilities of any material generally considered for power devices [63]. However, there are several aspects of C (diamond) that make it less than ideal. First, the material and device fabrication technology is much less mature and developed than for SiC and GaN. Second, the CTE for diamond is very low. Comparing the value of 0.8 ppm/K to typical package material CTEs, there is a clear thermomechanical mismatch. This may be offset by the extremely high thermal conductivity and the future possibility of integrating diamond substrates directly with diamond-based semiconductor devices to eliminate the mechanical stresses.

Another problem for diamond is the relatively large activation energies required for common impurity dopant species such as boron and phosphorous. For example, at room temperature, $<0.1\%$ of the impurity atoms of boron are ionized [64]. Thus, low resistivity diamond material is difficult to achieve.

Despite these issues, Schottky diodes are reported at multi-kV breakdown values [65]; and unipolar devices are fabricated by using a hydrogen-terminated diamond surface to create a hole accumulation layer, thus avoiding the activation energy problem [66].

Hydrogenated diamond surfaces, which exhibit a negative electron affinity (NEA), are also shown to be useful in vacuum field emission devices. In solids, the electron affinity is the energy difference between the vacuum energy and the conduction band minimum. The electron affinity can be thought of as the energy difference between the minimum of the conduction band and the vacuum level. By adding hydrogen at the diamond surface, the conduction band minimum can be raised above the vacuum level, thus allowing electrons to escape the semiconductor. This condition results in negative electron affinity. The NEA could be further exploited to develop high current and high power devices. One lateral diamond emitter diode is shown to deliver 6 μA at an applied anode-cathode voltage of 25 V [67]. This corresponds to a current density on the order of 150 A/cm^2.

D. Carbon, Boron, and Nitrogen

Other wide bandgap materials are theorized or developed with limited success so far. Some of these include a hypothetical form of cubic carbon nitride (c-C_3N_4) that would be an indirect bandgap material with a gap energy of 6.4 eV [68]. A similar material system is conjectured using Si and N (c-Si_3N_4). Small field effect transistor (FET) electronic devices made from thin-film CN_x are demonstrated to operate at V_{DS} of 60 V and I_D of 4.5 mA [69]. The cubic form of BN is successfully doped as a p-type and an n-type when grown on diamond films [70]. Further, junction diodes are fabricated from c-BN using beryllium and silicon as the p-type and n-type dopant species, respectively [71]. The cubic form of BN is an indirect semiconductor with a bandgap energy of 6.4 eV and a thermal conductivity of 1300 W/m/K. The hexagonal polytype, h-BN, is a direct band semiconductor with bandgap energy of ~5.9 eV [72].

Using lasers in nanofabrication offers unique capabilities involving both photothermal and photochemical processes. Projecting laser radiation on material surfaces leads to the formation of various nanostructures and causes a variety of effects, including localized heating, melting, ablation, decomposition, and photochemical reaction. It is possible to purposely deliver energy to a target material via a wide spectrum of laser wavelengths. Resonant excitation provides photons of matching energy that interact with the target material, e.g., laser-induced bond breaking and bond-selective chemical reactions. Laser beams can be easily manipulated to stimulate the development of mask-free direct laser writing of nanostructures. Using laser beams for extremely intense energy delivery results in an incomparable cold-wall rapid thermal processing technique. In addition, laser-material interactions dependent on polarization provide unique possibilities for the controllable fabrication of nanostructures [15]. Several carbon material structures are of particular interest, such as carbon nanotubes (CNTs).

CNTs have many desirable conducting properties and will continue to evolve into the future. Single-walled CNTs have an energy bandgap that varies inversely with the tube diameter [15]. This could allow easily variable heterojunction devices that have no interface states such as occur when compound semiconductors are used for similar devices (e.g., GaN/AlGaN). An FET device is fabricated using CNTs [73]. The cross section is shown below in Fig. 7. An 800-nm layer of SiO_2 is irradiated with electrons at a low dose and energy hence the CNT is not damaged, but negative fixed charges are inserted into the oxide surface near the CNT. Applying a gate voltage on the backside of the oxide controlled the current flow along the CNT. Look for more and more electronic devices to have an underlayment of CNT, or other carbon material form, in the future.

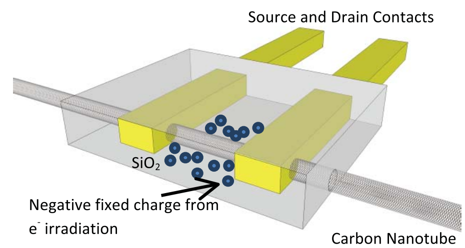

Fig. 7. FET design using CNT for the conduction channel. Captured negative charge at oxide surface from electron irradiation. Gate voltage is applied on the backside of oxide layer.

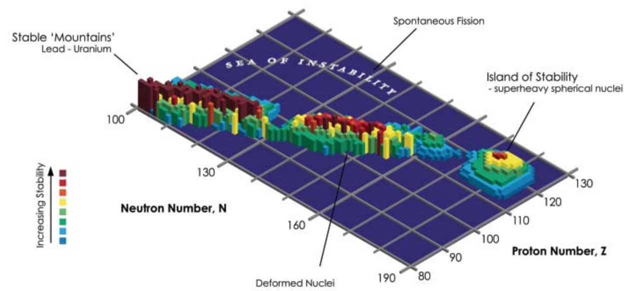

Fig. 8. Theorized island of stability for superheavy elements with atomic number near 120. User:Example/Wikipedia Commons/CC-BY-SA-3.0.

V. Future or Science Fiction?

Generally, as the number of protons and neutrons increases in atomic nuclei, the stability of the nucleus decreases. For example, adding ten protons and four neutrons to ^{238}U decreases the alpha-decay period by 16 orders of magnitude. Simple extrapolation leads to a size limit in atomic nuclei beyond which the forces of radioactive decay dominate prior to possible nuclear synthesis. This type of modeling led to the belief that nuclei beyond an atomic number (Z) of 104 could not stably exist.

Recent refinement of the understanding of how nuclei form energy shells (similar to electron energy shells) of allowed states indicates that superheavy nuclei with $Z > 104$, along with neutrons numbering around 184, can produce elements with half-lives of millions of years [74]. The postulated superheavy nuclei create new nuclear shells that increase the binding energy in the ground state of the nucleus that causes an increase in the energy barrier to fission. As shown in Fig. 8, the region mapped out in terms of the number of protons and neutrons indicates an island of stable nuclei/elements, as described by nuclear physicists. It may be that in the future, superheavy chemistry will result in new materials applicable to power electronic devices and their packaging.

It may also be theorized that in the far future, organic-like materials (such as biological devices) could conduct and control electric power far beyond what is currently possible in present-day organic electronics. One of the most attractive attributes would be the ability to self-heal damage caused by operational or environmental factors. If the constituent elements required for the organic power device of the future are hydrogen, oxygen, carbon, and maybe nitrogen, then growing replacement sections would mean feedstock elements would be readily available.

VI. Conclusion

Future Si devices will continue with incremental improvements in performance and reliability. As substrate material quality improves, SiC and GaN devices will also increase in capability and reliability. Other material systems, from nitrides of various sorts to carbon (such as diamond and CNT) await continued progress in fabrication technology before any real device structures can be realized. However, it was not at all clear that economics would favor any non-Si devices until the technological edge of this foundational electronic material truly reaches its physical limits.

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