A Survey of Semiconductor Devices

Kwok K. Ng, *Senior Member, IEEE*

***Abstract*—This paper attempts to present a complete collection of semiconductor devices. A total of 67 "major" devices have been identified, together with about 110 device variations which are considered to be "related" devices to the former. These devices are organized into groups and subgroups for a better overview, and the justification for such classification is discussed. After the list is presented, the author offers some comments and observations from his viewpoint.**

I. Introduction

SEMICONDUCTOR devices are the basic components of integrated circuits and are responsible for the startling rapid growth of the electronics industry in the past 50 years worldwide. Because there is a continuing need for faster and more complex systems for the information age, existing semiconductor devices are being constantly studied for improvement, and new ones are being invented. Whether it is for higher speed, lower power, higher density, higher efficiency, or new functionality, the number and types of semiconductor devices have been growing steadily in this fascinating field. There now exists approximately 100 semiconductor devices, depending on the definition of device [1]. The purpose of this paper is to collect the complete list of semiconductor devices, and to present them in a hierarchy of groups for a better overview.

II. Complete Device List and Classification

We first discuss what is qualified to be called an individual semiconductor device, as opposed to a device variation. Fig. 1 shows that, for example, LED, laser, solar cell, and tunnel diode are all composed of a p-n junction. Do we call them different devices, or just variations of the same device? Since each of these is made for a special purpose, their designs consider different device physics, and their physical structures are also very different. The emphasis of a solar cell, which receives light and converts it into electrical power, is very different from how a p-n junction emits light in an LED. There is probably little argument that LED, laser, solar cell, and tunnel diode are considered individual devices. Similarly, there are many kinds of field-effect transistors, and MOSFET, MESFET, MODFET, etc., can be recognized as separate devices. The next level of variations is more subtle. For example, a zener diode is a p-n junction rectifier with a special doping profile to give a well-defined reverse breakdown voltage, and a varactor is also a p-n junction with special consideration as a variable capacitor. Similarly, a thin-film transistor (TFT) is generally referred to a MOSFET made from deposited thin-films, and double-diffused MOS (DMOS) transistor uses a special technique to make MOSFET of short channel length. These devices have only slight variations in structure and operation, and thus can be considered as minor device variations. It is for these reasons that a total of 67 "major" devices are identified. The next level of variations gives roughly another 110 device structures which will be attached to these major devices as "related" devices. This arrangement, of course, can change with time depending on the development and relative significance of each device structure.

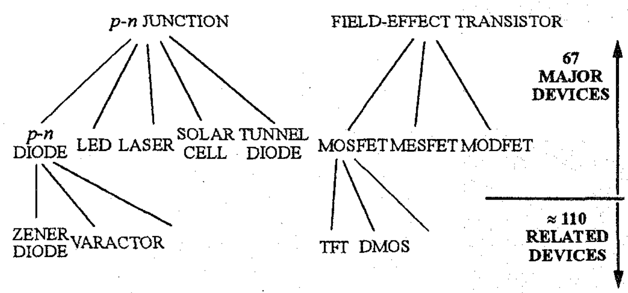

Fig. 1. Hierarchy of semiconductor devices. Minor variations are labeled as "related devices."

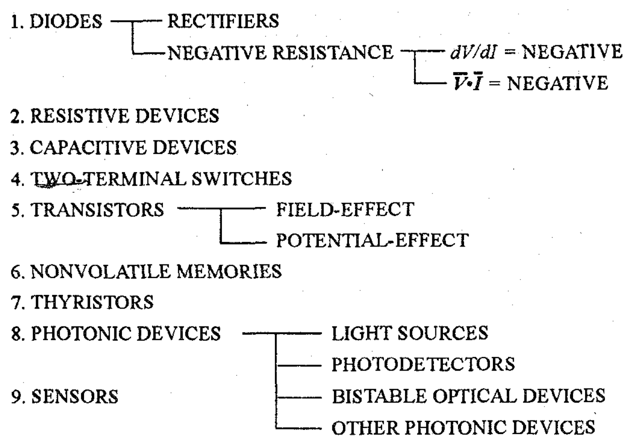

Fig. 2. Semiconductor devices by groups, organized either by function or by structure.

To help gain a better perspective, semiconductor devices are ordered into groups, with group names assigned to describe their functions or structures. These groups are shown in Fig. 2 as 1) diodes, 2) resistive devices, 3) capacitive devices, 4) two-terminal switches, 5) transistors, 6) nonvolatile memories, 7)

Manuscript received March 10, 1996; revised April 19, 1996.
The author is with Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974-0636 USA.
Publisher Item Identifier S 0018-9383(96)07220-6.

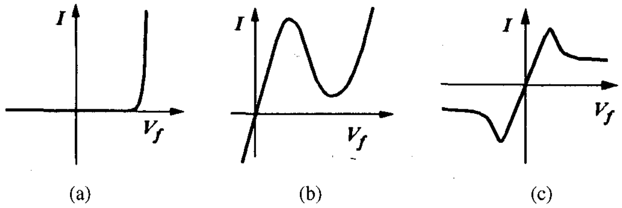

Fig. 3. The (a) traditional rectifying characteristics of a diode are no longer applicable for (b) the tunnel diode, and (c) the Gunn diode.

thyristors, 8) photonic devices, and 9) sensors. It should be pointed out that while most of the device names are more-or-less established in literature, their classification can probably be done in different fashions. What is presented in this paper is just one approach, the main function of which is to serve as a tool to help in digesting the vast number of devices that exist. Table I presents all major and related devices organized in such a scheme. It is the purpose not to ignore devices that became obsolete since they are often grounds for new concepts, and also to avoid duplication of past efforts.

While most of these group names are self-explanatory, a few need clarification. The name "diode" comes from vacuum tubes, and is referred to a two-element diode tube. Other vacuum tubes are the triode tube, tetrode tube, and pentode tube, with the number of electrodes being 3, 4, and 5, respectively. Since the cathode in vacuum tubes emits only one kind of carriers (electrons), the diode tube has asymmetric I–V behavior and is a rectifier. Although semiconductor diodes inherited the name, some of them actually do not have rectifying characteristics. Examples are the tunnel diode and the Gunn diode (Fig. 3). In day-to-day dictionaries, a diode is defined as "an electronic device that restricts current flow chiefly to one direction" [2] or "a rectifier that consists of a semiconducting crystal with two terminals ..." [3], clearly indicating a rectifier in both. Such definition is no longer valid in light of devices such as tunnel diode and Gunn diode. A more up-to-date definition of diode can be found in [4] as "a semiconductor device having two terminals and exhibiting a nonlinear voltage-current characteristic." Basically, any two-terminal device that has nonlinear I–V characteristics is a diode, or any two-terminal current-carrying device that is not a resistor is a diode. It is rather unfortunate to see that the term diode does not carry much meaning anymore. Rectifiers are, therefore, only a subgroup of diodes. Another subgroup of diodes that is distinctively different from rectifiers is the one having negative differential resistance. Within this subgroup of negative-resistance devices, there are two types: one that has a negative dV/dI regime, and the transit-time devices where the negative resistance is due to the small-signal voltage and current that are out of phase with each other.

A switch, in semiconductor terms, is a device that has two states: a low-impedance (on) state and a high-impedance (off) state. Switching between these two states can be controlled by voltage, current, temperature, light, or a third terminal. Many types of devices can be called a switch (Fig. 4). A transistor, for example, is considered a three-terminal switch, especially in digital circuits. Thyristors are also a special kind of switch.

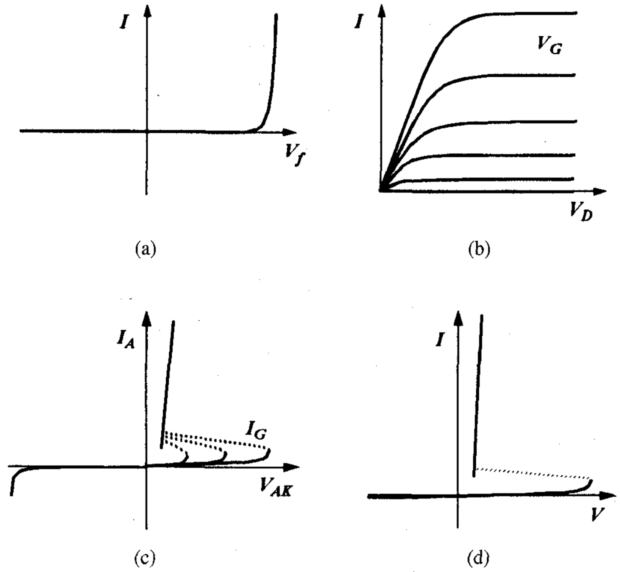

Fig. 4. Different devices that can be called switches. Examples are: (a) rectifier, (b) transistor, (c) thyristor, and (d) two-terminal switch.

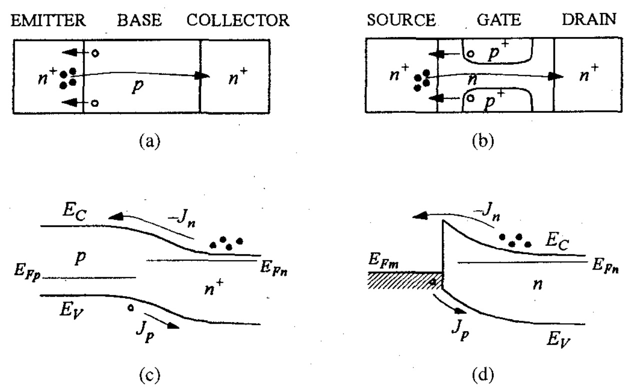

Fig. 5. Similarity in carrier currents between (a) a bipolar transistor and (b) an enhancement JFET, and also between (c) a one-sided p-n junction, and (d) a Schottky barrier.

They are included in a separate group from switches based on that they usually contain p-n-p-n layers, have more than two terminals, and are used mainly as power devices. The group of two-terminal switches are distinguished from the negative-resistance diodes, like tunnel diode, by having S-shape I–V curves as opposed to N-shape curves [Fig. 3(b)].

Unlike diode, transistor (transfer-resistor) was a new name coined at the beginning of the semiconductor era for the bipolar transistor, instead of keeping the old equivalent of triode. In the classification of devices here, we do not follow the common approach in literature to divide devices into "bipolar" and "unipolar" types. For transistors, the bipolar transistor has been used as a representative of the first type, and MOSFET and JFET of the second type. The reason behind that classification is for a bipolar transistor, the base current is due to one type of carriers while the emitter-collector current is of the opposite type; thus both types of carriers are involved. For a MOSFET, the gate current is negligible, and the carriers in the channel are the only kind responsible for the current flow.

TABLE I
A COMPLETE LIST OF SEMICONDUCTOR DEVICES, INCLUDING ALIASES AND ACRONYMS. DEVICE NAMES FOLLOWING NUMBERS IN PARENTHESES ARE RELATED DEVICES (AFTER [1])

DIODES: I–RECTIFIERS

1. ***p-n* Junction Diode.**
(1) Zener diode. (2) Step-recovery diode, fast-recovery diode, snap-off diode, snap-back diode. (3) Anisotype heterojunction. (4) Varactor, varactor diode, varicap diode.
2. ***p-i-n* Diode.**
3. **Schottky-Barrier Diode,** point-contact, metal-semiconductor junction, surface-barrier diode, hot-carrier diode, hot-electron diode.
(1) Mott barrier. (2) Metal-insulator-semiconductor (MIS) tunnel diode.
4. **Planar-Doped-Barrier (PDB) Diode,** δ-doped-barrier diode, triangular-barrier diode, bulk-barrier diode, bulk unipolar diode.
(1) Camel diode.
5. **Isotype Heterojunction.**
(1) Graded-composition barrier.

DIODES: II–NEGATIVE RESISTANCE

6. **Tunnel Diode,** Esaki diode.
(1) Backward diode, back diode.
7. **Transferred-Electron Device (TED),** Gunn diode, transferred-electron oscillator (TEO), transferred-electron amplifier (TEA).
8. **Resonant-Tunneling Diode,** double-barrier diode.
9. **Real-Space-Transfer (RST) Diode.**
10. **Impact-Ionization-Avalanche Transit-Time (IMPATT) Diode,** Read diode, Misawa diode.
(1) Trapped-plasma avalanche-triggered transit (TRAPATT) diode.
(2) Double-velocity avalanche transit-time (DOVATT) diode.
(3) Mixed-tunnel-avalanche transit-time (MITATT) diode.
11. **Barrier-Injection Transit-Time (BARITT) Diode,** punch-through diode.
(1) Double-velocity transit-time (DOVETT) diode. (2) Tunnel-injection transit-time (TUNNETT) diode. (3) Quantum-well-injection transit-time (QWITT) diode.

RESISTIVE DEVICES

12. **Resistor.**
(1) Varistor. (2) Potentiometer, pot, rheostat. (3) *n-i-n* diode, *p-i-p* diode, double-junction diode.
13. **Ohmic Contact.**

CAPACITIVE DEVICES

14. **Metal-Oxide-Semiconductor (MOS) Capacitor.**
(1) Metal-insulator-semiconductor (MIS) capacitor. (2) Parallel-plate capacitor.
15. **Charge-Coupled Device (CCD),** charge-transfer device (CTD).
(1) Buried-channel charge-coupled device (BCCD). (2) Peristaltic charge-coupled device (PCCD). (3) Profiled-peristaltic charge-coupled device (P^2CCD). (4) Bucket-brigade device (BBD).

TWO-TERMINAL SWITCHES

16. **Metal-Insulator-Semiconductor Switch (MISS),** MIS switch, MIS thyristor (MIST).
(1) Metal-insulator-semiconductor-metal (MISM) switch. (2) Metal-insulator-semiconductor-insulator-metal (MISIM) switch.
17. **Planar-Doped-Barrier (PDB) Switch,** triangular-barrier switch.
(1) Polysilicon-*n-p* switch. (2) Double-heterostructure optoelectronic switch (DOES), ledistor, lasistor.
18. **Amorphous Threshold Switch,** ovonic threshold switch.
(1) Amorphous memory switch, ovonic memory switch.

TRANSISTORS: I–FIELD-EFFECT

19. **Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET),** insulated-gate field-effect transistor (IGFET), metal-oxide-silicon field-effect transistor (MOSFET), metal-oxide-semiconductor transistor (MOST).
(1) Double-diffused metal-oxide-semiconductor (DMOS) transistor. (2) Hexagonal field-effect transistor (HEXFET). (3) V-groove (or vertical) metal-oxide-semiconductor (VMOS) transistor. (4) U-groove metal-oxide-semiconductor (UMOS) transistor. (5) Thin-film transistor (TFT). (6) Metal-insulator-semiconductor field-effect transistor (MISFET). (7) Pressure-sensitive field-effect transistor (PRESSFET). (8) Gate-controlled diode, gated diode.
20. **Junction Field-Effect Transistor (JFET),** junction-gate field-effect transistor.
(1) V-groove field-effect transistor (VFET).
21. **Metal-Semiconductor Field-Effect Transistor (MESFET).**
22. **Modulation-Doped Field-Effect Transistor (MODFET),** high-electron-mobility transistor (HEMT), two-dimensional electron-gas field-effect transistor (TEGFET), selectively-doped heterojunction transistor (SDHT), heterojunction field-effect transistor (HFET).
(1) Inverted heterojunction field-effect transistor, inverted MODFET. (2) Planar-doped (delta-doped, pulse-doped) heterojunction field-effect transistor. (3) Single-quantum-well heterojunction field-effect transistor, double-heterojunction field-effect transistor (DHFET).
(4) Superlattice heterojunction field-effect transistor.
(5) Pseudomorphic heterojunction field-effect transistor.
(6) Heterojunction insulated-gate field-effect transistor (HIGFET).
(7) Semiconductor-insulator-semiconductor field-effect transistor (SISFET). (8) Doped-channel heterojunction field-effect transistor.
23. **Permeable-Base Transistor,** metal-gate transistor.
24. **Static-Induction Transistor (SIT),** analog transistor, multi-channel field-effect transistor, gridistor, bipolar-mode static-induction transistor, depleted-base transistor.
25. **Planar-Doped Field-Effect Transistor,** delta-doped (δ-doped) field-effect transistor, pulse-doped field-effect transistor.
26. **Lateral Resonant-Tunneling Field-Effect Transistor (LRTFET).**
27. **Stark-Effect Transistor.**
28. **Velocity-Modulation Transistor (VMT).**

TRANSISTORS: II–POTENTIAL-EFFECT

29. **Bipolar Transistor,** junction transistor, point-contact transistor.
(1) Heterojunction bipolar transistor (HBT), double-heterojunction bipolar transistor (DHBT). (2) Darlington amplifier. (3) Tunneling-emitter bipolar transistor.
30. **Tunneling Hot-Electron-Transfer Amplifier (THETA),** metal-oxide-metal-oxide-metal (MOMOM), metal-insulator-metal-insulator-metal (MIMIM), metal-oxide-metal-semiconductor (MOMS), metal-insulator-metal-semiconductor (MIMS), metal-oxide-*p-n* (MO*p-n*), metal-insulator-*p-n* (MI*p-n*).
31. **Metal-Base Transistor,** semiconductor-metal-semiconductor (SMS) transistor.
32. **Real-Space-Transfer (RST) Transistor,** negative-resistance field-effect transistor (NERFET), charge-injection transistor (CHINT).
33. **Bipolar Inversion-Channel Field-Effect Transistor (BICFET).**
(1) Bulk-barrier transistor, bulk unipolar transistor.
34. **Tunnel-Emitter Transistor (TETRAN),** inversion-base bipolar transistor.
(1) Surface-oxide transistor.
35. **Planar-Doped-Barrier Transistor.**
(1) Camel transistor. (2) Field-effect hot-electron transistor.
36. **Heterojunction Hot-Electron Transistor.**
37. **Induced-Base Transistor.**
38. **Resonant-Tunneling Bipolar Transistor (RTBT/RBT).**
39. **Resonant-Tunneling Hot-Electron Transistor (RHET).**
40. **Quantum-Well-Base Resonant-Tunneling Transistor (QWBRTT).**

The author, however, feels that the classification based on this bipolar-unipolar terminology is not clear, and may even be incorrect. Specifically, in a bipolar transistor, the base current is a sort of leakage current which is not useful (Fig. 5). It is only a byproduct of a base potential needed to modulate the emitter-collector current. If this base current is somehow made to zero, the bipolar transistor would still work, and work even better. In fact, the main purpose of a heterojunction bipolar

TABLE I *(Continued)*

NONVOLATILE MEMORIES

41. **Floating-Gate Avalanche-Injection Metal-Oxide-Semiconductor (FAMOS) Transistor.**
(1) Floating-gate tunnel-oxide (FLOTOX) transistor.

42. **Metal-Nitride-Oxide-Semiconductor (MNOS) Transistor,** metal-nitride-oxide-silicon transistor, metal-insulator-oxide-semiconductor (MIOS) transistor.
(1) Metal-oxide-nitride-oxide-semiconductor (MONOS) transistor, silicon-oxide-nitride-oxide-semiconductor (SONOS) transistor.
(2) Ferroelectric field-effect transistor (FEFET).

THYRISTORS

43. **Silicon-Controlled Rectifier (SCR),** thyristor, semiconductor-controlled rectifier.
(1) Gate-assisted-turn-off thyristor (GATT). (2) Gate-turn-off (GTO) thyristor. (3) Asymmetric thyristor, asymmetric SCR. (4) Reverse-conducting thyristor (RCT). (5) Breakover diode, Shockley diode, four-layer diode, *p-n-p-n* diode. (6) Diode AC switch (DIAC). (7) Triode AC switch (TRIAC). (8) Light-activated thyristor, light-triggered thyristor, light-activated SCR (LASCR). (9) Programmable unijunction transistor (PUT). (10) Silicon-controlled switch (SCS). (11) Silicon unilateral switch (SUS). (12) Silicon bilateral switch (SBS). (13) MOS-controlled thyristor.

44. **Insulated-Gate Bipolar Transistor (IGBT),** insulated-gate transistor (IGT), insulated-gate rectifier (IGR), conductivity-modulated field-effect transistor (COMFET), gain-enhanced metal-oxide-semiconductor field-effect transistor (GEMFET), bipolar field-effect transistor (BiFET), injector field-effect transistor, lateral insulated-gate transistor (LIGT).

45. **Unijunction Transistor,** filamentary transistor, double-base diode.

46. **Static-Induction Thyristor (SIThy),** field-controlled thyristor.

LIGHT SOURCES

47. **Light-Emitting Diode (LED).**
(1) Superluminescent diode, superradiant LED.

48. **Injection Laser,** junction laser, laser diode.
(1) Heterojunction laser, double-heterojunction (DH) laser, channeled-substrate planar laser, buried-heterojunction laser. (2) Large-optical-cavity (LOC) laser. (3) Separate-confinement heterojunction (SCH) laser, graded-index separate-confinement heterojunction (GRIN-SCH) laser. (4) Quantum-well laser, multiple-quantum-well laser, superlattice laser. (5) Cleaved-coupled-cavity (C^3) laser. (6) Distributed-feedback laser, distributed-Bragg-reflector laser. (7) Vertical-cavity surface-emitting laser (VCSEL).

PHOTODETECTORS

49. **Photoconductor,** photoresistor, photoconductive cell, photocell.
(1) Photoelectromagnetic (PEM) detector. (2) Free-carrier photoconductor, hot-electron photoconductor, hot-electron bolometer. (3) Putley detector. (4) Dember-effect detector.

50. ***p-i-n* Photodiode.**
(1) *p-n* photodiode. (2) Nuclear-radiation detector, radiation detector, particle detector, nuclear detector, lithium-drifted detector.

51. **Schottky-Barrier Photodiode,** metal-semiconductor photodiode, point-contact photodiode.

52. **Charge-Coupled Image Sensor (CCIS),** charge-transfer image sensor (CTIS), metal-oxide-semiconductor (MOS) photodetector, metal-insulator-semiconductor (MIS) photodetector.
(1) Charge-injection device (CID).

53. **Avalanche Photodiode (APD).**
(1) Separate-absorption-multiplication avalanche photodiode (SAM-APD), separate-absorption-graded-multiplication avalanche photodiode (SAGM-APD). (2) Superlattice avalanche photodiode. (3) Staircase avalanche photodiode.

54. **Phototransistor.**
(1) Darlington phototransistor, photo-Darlington. (2) Avalanche phototransistor. (3) Photosensitive field-effect transistor, photo-FET. (4) Bulk-barrier phototransistor, planar-doped-barrier photodiode, triangular-barrier photodiode, modulated-barrier photodiode. (5) Static-induction phototransistor. (6) Tunnel-emitter phototransistor.

55. **Metal-Semiconductor-Metal (MSM) Photodetector.**

56. **Quantum-Well Infrared Photodetector (QWIP).**

57. **Negative-Electron-Affinity (NEA) Photocathode,** NEA photoemitter, photocathode tube, photoemissive tube, vacuum photodiode.
(1) Photomultiplier. (2) Transferred-electron photocathode.

58. **Photon-Drag Detector.**

BISTABLE OPTICAL DEVICES

59. **Self-Electrooptic-Effect Device (SEED).**

60. **Bistable Etalon,** nonlinear (or bistable) Fabry-Perot resonator (or interferometer).
(1) Interference filter.

OTHER PHOTONIC DEVICES

61. **Solar Cell.**

62. **Electroabsorption Modulator.**
(1) Optical waveguide.

SENSORS

63. **Thermistor,** thermally-sensitive resistor.
(1) Resistance temperature detector (RTD). (2) Thermistor bolometer. (3) Pyroelectric detector.

64. **Hall Plate,** Hall generator, magnetometer, gaussmeter.
(1) Magnetoresistor. (2) Magnetodiode. (3) Magnetotransistor, magnistor. (4) Magnetic-field-sensitive field-effect transistor (MAGFET). (5) Carrier-domain magnetic-field sensor. (6) Magnetostrictive transducer.

65. **Strain Gauge (Gage).**
(1) Piezoelectric strain gauge.

66. **Interdigital Transducer (IDT),** surface-acoustic-wave (SAW) transducer.

67. **Ion-Sensitive Field-Effect Transistor (ISFET),** chemically-sensitive field-effect transistor (CHEMFET).
(1) Enzyme field-effect transistor (ENFET). (2) Ion-controlled diode. (3) Semiconducting-oxide sensors. (4) Catalytic-metal sensors. (5) Open-gate field-effect transistor (OGFET). (6) Adsorption field-effect transistor (ADFET), surface-accessible field-effect transistor (SAFET), suspended-gate field-effect transistor (SGFET). (7) Charge-flow transistor.

transistor is to suppress this base current, without affecting the main current. Next, let us consider an enhancement JFET. To turn the transistor on, the p-n junction gate is forward biased. This injects minority carriers into the channel. The enhancement JFET is therefore as "bipolar" as the bipolar transistor. This argument can also be extended to two-terminal devices. A p-n junction has been referred to as a bipolar device while a Schottky barrier as a unipolar device. For practical p-n junctions, they are usually one-sided in that one side is much more heavily doped than the other. A typical Si p-n junction

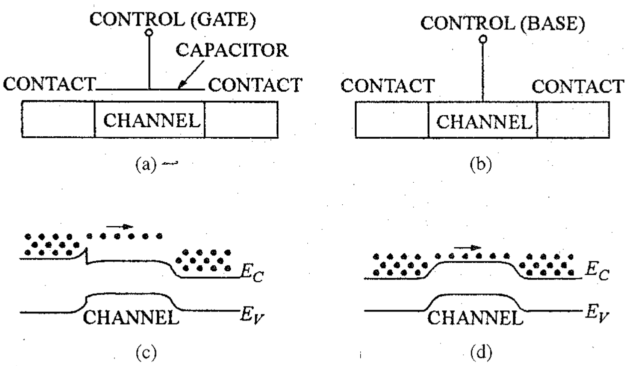

Fig. 6. (a) In an FET the channel is controlled indirectly via a capacitor. (b) In a PET the channel is controlled by a direct contact. (c) An HET is characterized by having energetic carriers in the channel as opposed to the condition in (d) regular FET and PET.

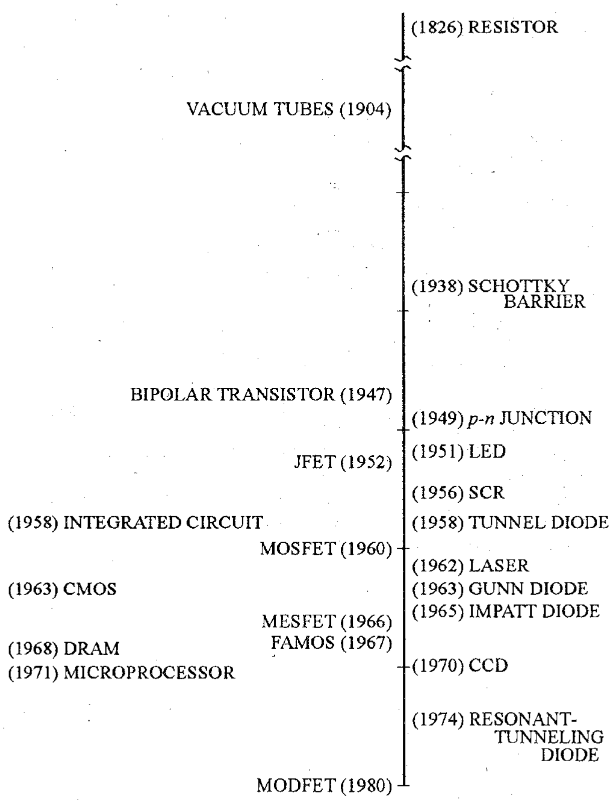

Fig. 7. Some major milestones of semiconductor devices. Milestones at left are circuit related.

has doping levels of 10^{20} cm^{-3} and 10^{16} cm^{-3}, and the ratio of the two types of current is $\approx 10^{-4}$. For a practical Schottky-barrier diode, even though the current is dominated by majority carriers, the minority-carrier current is not zero. It is a factor of $\approx 10^{-4}$–10^{-6} (injection efficiency) smaller. As seen from these diodes, the transition from a bipolar device to a unipolar device is not clear.

Here transistors are divided into two groups, following the notation used in [5]. These are field-effect transistor (FET) and potential-effect transistor (PET). The field effect is defined, originally by Shockley when the first field-effect transistor

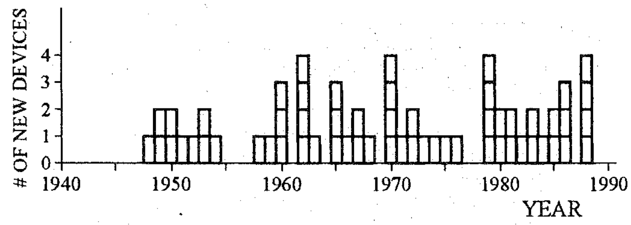

Fig. 8. Number of new devices reported per year between 1940–1990.

TABLE II
CURRENT-CONDITION MECHANISMS OF SEMICONDUCTOR DEVICES

Mechanisms	Examples
Drift	Resistor, most FETs
Diffusion	*p-n* junction, bipolar transistor
Thermionic emission	Schottky barrier, PDB diode
Tunneling	Tunnel diode, ohmic contact
Recombination	LED, *p-i-n* diode
Generation	Solar cell, photodetectors
Avalanche	IMPATT diode, Zener diode

(JFET) was envisaged, as a process "in which the conductivity of a layer of semiconductor is modulated by a transverse electric field" [6]. An FET differs from a PET in that its channel is controlled capacitively by transverse electric field while in a PET, the channel's potential is accessed by a direct contact. This distinction is illustrated in Fig. 6(a) and (b). The capacitive coupling in an FET is via an insulator or a space-charge layer. One observation on FET's is that almost all have channel conduction by the drift process, and have a well-defined threshold voltage. There is another group of transistors called hot-electron transistors (HET's) whose emitting junction is a heterostructure such that the carriers in the channel have high potential or kinetic energy (Fig. 6(c)). Since a hot carrier has higher velocity, HET's are expected to have higher intrinsic speed, higher current, and higher transconductance. Although theoretically HET can be either an FET or PET, most HET's are special cases of PET's.

III. SOME OBSERVATIONS AND COMMENTS

For a historic perspective, some seminal electronic devices with the years they were developed are shown in Fig. 7. The earliest device, not necessarily made of semiconductor material, is probably the resistor, implied by Ohm's law back in 1826. Vacuum tubes started around 1904, and were the major electronic components in the early radio era through late-1940's. The real birth of the semiconductor industry was in 1947 with the invention of the bipolar transistor. Ever since, new semiconductor devices have been invented at quite a steady pace, although some are more commercially significant than others. Fig. 7 shows only the more common kinds. There are some devices whose development is too gradual to assign a birthday. An example is the solar cell. Starting from the mid-1970's, with the advent of MBE and MOCVD technologies, there are numerous heterostructure devices that are also omitted because it is too early for them to have a commercial impact. The number of new devices made per year

TABLE III
PARAMETERS PERTAINING TO THE SPEED OF A TRANSISTOR, USING FET AS AN EXAMPLE. C_G, C_{ip}, C_{out}, C_{run}, AND C_{load} ARE THE CAPACITANCES OF THE INTRINSIC GATE, INPUT PARASITICS, OUTPUT, RUNNER, AND LOAD, RESPECTIVELY

Parameters	Considerations	Speed figure-of-merit of FET
Transit time	Intrinsic, no capacitance	g_m/C_G
S-parameters (f_T)	No output capacitance, no runner	$g_m/(C_G+C_{ip})$
(f_{max})	Optimized load, no runner	
Ring oscillator	Fan-out = 1, short runner	$g_m/(C_G+C_{ip}+C_{out})$
Real circuit	Multiple fan-outs, long runner, load capacitance	$g_m/(C_G+C_{ip}+C_{out}+C_{run}+C_{load})$

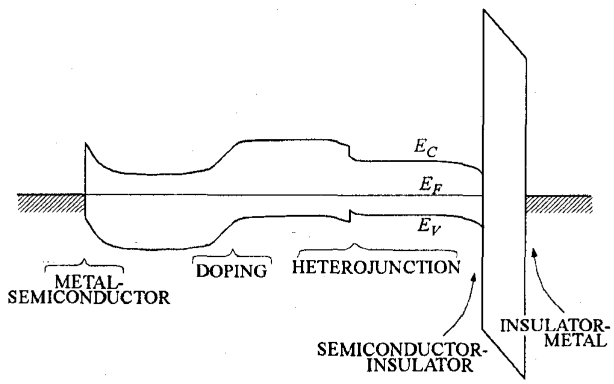

Fig. 9. Energy-band diagram showing the five interfaces as basic device building blocks.

is shown in Fig. 8. It can be seen that the growth rate of new devices is quite steady. One observation is that new devices in the 1980's are made either with planar-doped barriers or with heterostructures.

Semiconductor devices can be viewed as consisting of device building blocks. In spite of the large number of devices, there are only five building blocks, which are interfaces of two materials or doping types. These fundamental interfaces are all included in the energy-band diagram of Fig. 9. They are, from left to right, metal-semiconductor interface, doping interface, heterojunction, semiconductor-insulator interface, and insulator-metal interface. The metal-semiconductor interface, known as the Schottky barrier, also includes the ohmic contact which is inevitable in every semiconductor device. The doping interface also includes the planar-doped barrier. The heterojunction is also the basis for quantum-well devices. A bipolar transistor, for example, is built of two p-n junctions. A MOSFET has two p-n junctions, one semiconductor-insulator interface, and one insulator-metal interface. From the processing point of view, the available tools are: metallization for metal-semiconductor and insulator-metal interfaces, implantation or diffusion for doping, epitaxy for heterojunction, and oxidation or deposition for semiconductor-insulator interface.

Since the compositions vary among semiconductor devices, their current-conduction mechanisms also vary accordingly. All the current-conduction mechanisms are summarized in Table II for an overview. These currents are due to drift, diffusion, thermionic emission, tunneling, recombination, generation, and avalanche. The space-charge-limited current is not included in the table since there is no device whose main function relies on this current.

Finally, we discuss what is meant by the recent, commonly used term high-speed device. Is it a device that has intrinsically fast response, or is it one that enables a high-speed circuit? This is important to clarify since different criterion calls for a different device design. Table III summarizes the different parameters that are used to indicate the first-order estimate of the device speed, with a different amount of parasitics and loading taken into consideration. The most fundamental parameter is the transit time—the time it takes for the carriers to travel between the source-drain or emitter-collector terminals. Direct measurement of this parameter is extremely difficult. The next level is parameters deduced from two-port, small-signal S-parameter microwave measurement. This is done with a single device, and thus not as a circuit. It is the highest frequency that can be measured on the device, but certain parasitics are ignored. The cutoff frequency f_T, for example, is a current-gain measurement. The output is AC-shorted so that the output capacitance is not included. $f_{\max}$ includes the output capacitance but the load is matched to optimize the power transfer. The simplest circuit measurement is a ring oscillator. It is usually designed with a minimum fan-out of one, and minimum interconnect distance. A real circuit has much larger load capacitance as well as larger interconnect capacitance. From this viewpoint, if the circuit speed is to be optimized, the current drive or transconductance of a transistor is more important than the intrinsic response. It is possible to predict the ultimate circuit speed based on the transit time, microwave measurements, or ring-oscillator speed, but care has to be taken to account for realistic parasitics.

IV. CONCLUDING REMARKS

In conclusion, 67 "major" devices have been identified, with another ~110 variations included as "related" devices. These devices are organized into nine groups for a better perspective, so devices within each group can be compared more easily. All semiconductor devices are found to be built on five interfaces or device building blocks. Although most R&D efforts are recently put in device miniaturization, new semiconductor devices are still growing at a steady pace. In spite of the large number of devices, only a few percent dominates the electronics market, with MOSFET alone contributing 80% of the revenue. There is confusion with device terms such as diode, switch, unipolar/bipolar, etc. There are also cases where too many new device names are made for the same device, and the MODFET (also called HEMT, TEGFET, SDHT, etc.) is a good example. I ask that we device physicists try our best to keep device names simple and consistent before it gets much worse.

REFERENCES

[1] K. K. Ng, *Complete Guide to Semiconductor Devices.* New York: McGraw-Hill, 1995.

[2] *American Heritage Dictionary,* 2nd ed. New York: Houghton Mifflin, 1991.

[3] *Webster's Ninth New Collegiate Dictionary.* Springfield: Merriam-Webster, 1985.

[4] *The New IEEE Standard Dictionary of Electrical and Electronics Terms,* 5th ed. New York: IEEE, 1993.

[5] *High-Speed Semiconductor Devices,* S. M. Sze, Ed. New York: Wiley, 1990.

[6] W. Shockley, "A unipolar field-effect transistor," in *Proc. IRE,* 1952, vol. 40, p. 1365.

Kwok K. Ng (M'84–SM'89) received the Ph.D. degree from Columbia University, New York, NY, in 1979 and the B.S. degree from Rutgers University, New Brunswick, NJ, in 1975, both in electrical engineering.

He has been with Bell Laboratories, Lucent Technologies (formerly AT&T), Murray Hill, NJ, since 1980, engaging in different aspects of silicon VLSI devices and technologies. He is currently a technical manager of a BiCMOS group. He has published close to 40 papers, contributed to two book chapters, and holds five patents. He is author of the recent book, *Complete Guide to Semiconductor Devices.*

Dr. Ng is a Distinguished Lecturer of the IEEE Electron Devices Society, and serves in the Publication Committee. He was a technical committee member for Device Research Conference from 1986 to 1988, and an Associate Editor of IEEE ELECTRON DEVICE LETTERS in 1990 and 1991.