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Yoshiaki Daimon Hagihara

(1) Thank you, Anantha-san.

Good evening, ladies and gentlemen. And a happy 60th anniversary to ISSCC2013.

And a happy 60th anniversary to ISSCC2013.

I thought I was invited as an old boy for this special occasion since I had been involved and served for many years in this ISSCC community. But I received a homework and was asked to prepare for a short talk on this panel. It was a very difficult subject. So, the first thing I did was, look around for my old subject. So, the first thing I did was, look around for my old books and notebooks in my house and office.



*Digging lost treasures in circuit design  
out of my old books....*

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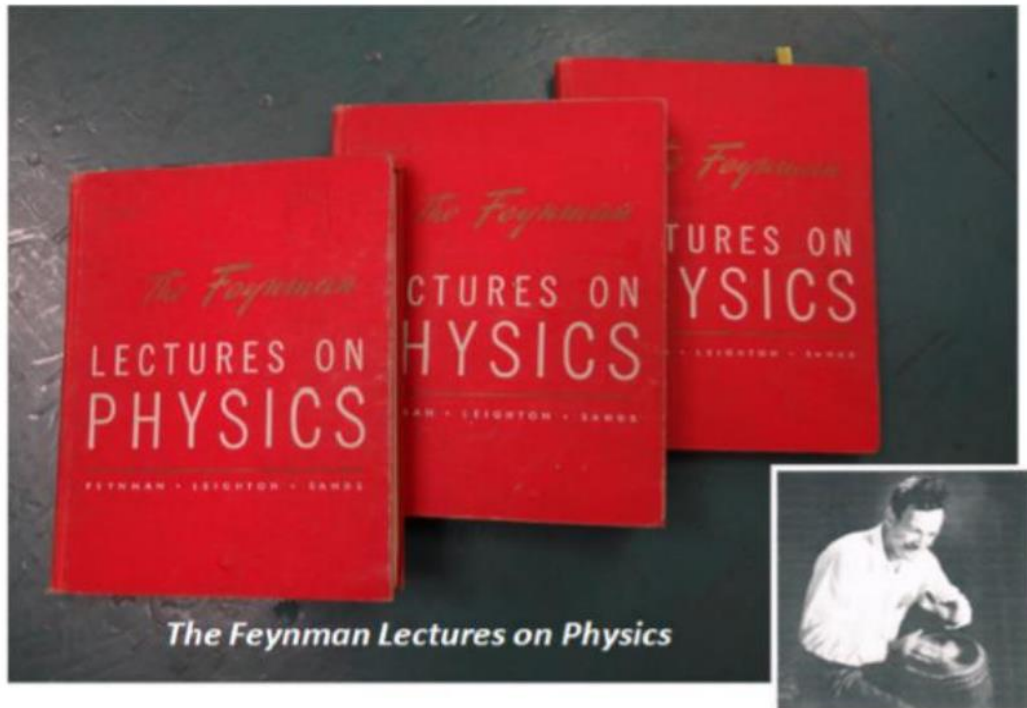
(2) I found some, I sorted them out, and put them together on my bookshelf.  
Here they are.

This evening, if I am allowed to introduce you only one unique circuit application, it would be a circuit application of a p-n-p-n diode structure. diode structure.

In a normal operation mode, this device works as a Thyristor, which can drive a large current and can make even a big linear motor car float and move very swiftly. On the other hand, when this is in off-state, it has very, very small leakage current, which is very important for our modern society seeking for low-power is very important for our modern society seeking for low-power Energy-saving systems.

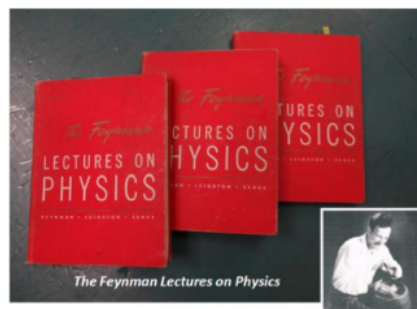
And in a dynamic operation mode, this device may work as a simple p-n-p-n capacitance, that can detect and store one single electron. I think this is a key device of an image sensor.





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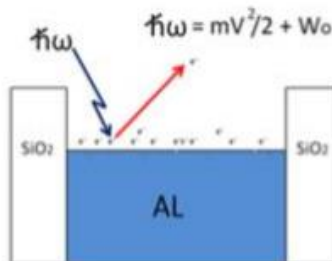
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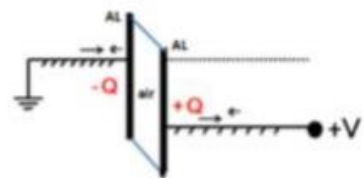
(3) There are many physics involved to understand this p-n-p-n diode structure and its related circuit behaviors.

So I tried to recall my freshman year in college, when I was taking a physics course. Prof. Leighton, and sometimes Prof. Feynman himself, gave us lectures. Their lectures were always fascinating to us. They always tried to appeal intuitively to our young minds.

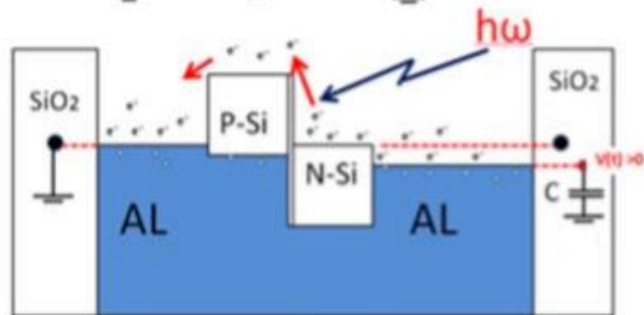
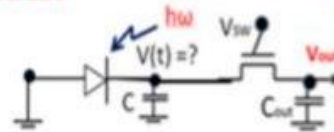
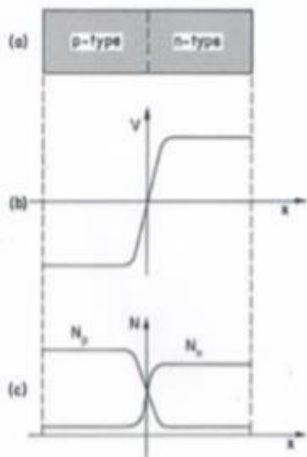
Feynman once said that an electron is always free, moving around rapidly in free space, even in a solid, and it never stops. It is very hard to catch. We don't know exactly where it is. Our civilization is based on the catch. We don't know exactly where it is. Our civilization is based on the technology of controlling a single electron.



Metal



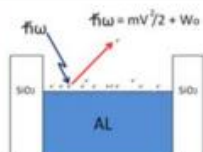
Capacitor



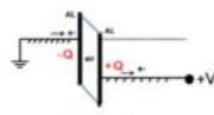
Diode

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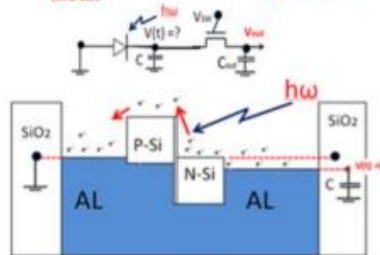
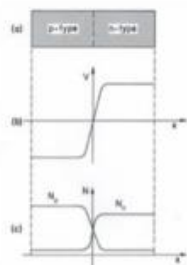
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Metal



Capacitor

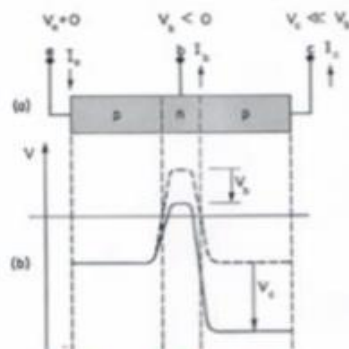


Diode

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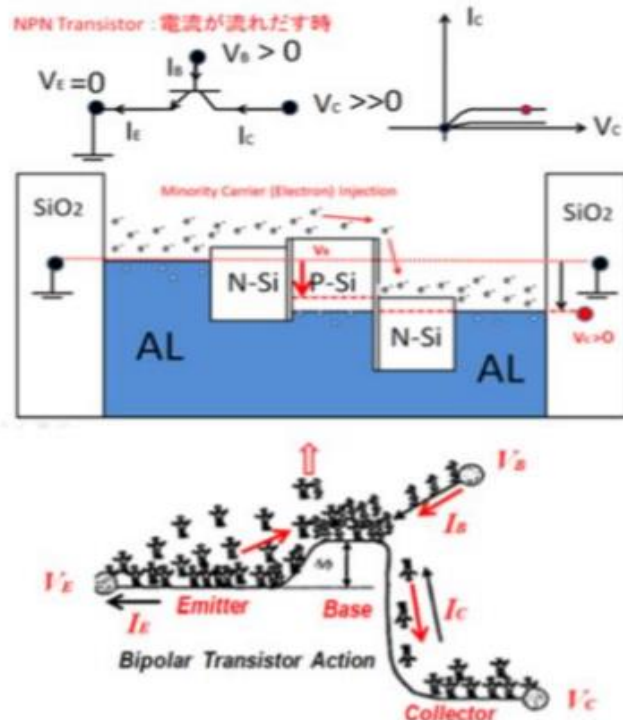
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(4) So I was always being guided to try to understand physics by paying a special attention to the behavior of one single electron interacting with a photon in a solid, in a metal, in an insulator, in a capacitor, in a p-n junction and in a transistor. A p-n junction is also called a diode, a rectifier, a LED, a solar cell or simply a p-n junction capacitor depending on how we want to use it. If we don't want to use, but if it is still there, I learned later that it is also called a parasitic p-n junction capacitance, which is a very important circuit element for predicting a very complicated VLSI circuit performance in some cases.

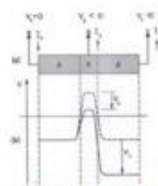


Bipolar Transistor

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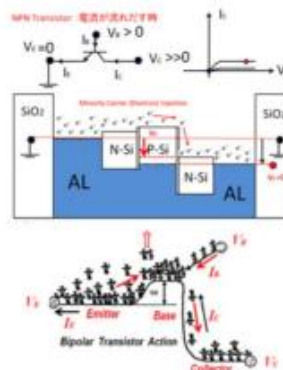


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Bipolar Transistor

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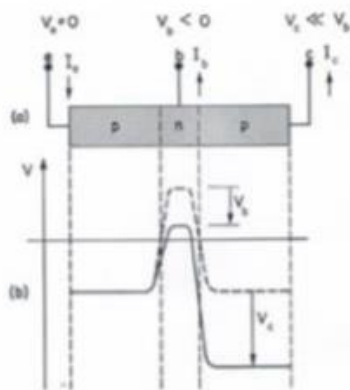


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(5) I thought I had a very good background in Feynman physics. Feynman physics always talked about the behavior of one single electron in free space and in a solid. The situation gets more complex when an electron interact with a photon. Well, a picture is worth one thousand words.

This is a picture of boys trying to catch a girl on the hill top but most of the boys are guided to the collector junction cliff and fall down to be collected at the collector terminal. And only a few boys out of say 100 energetic boys can catch a girl on the hill top and they can recombine can catch a girl on the hill top and they can recombine and become happy. And the pair can produce a baby-photon. This is in a sense a light emitting photo-transistor with a very poor efficiency of a few percents.

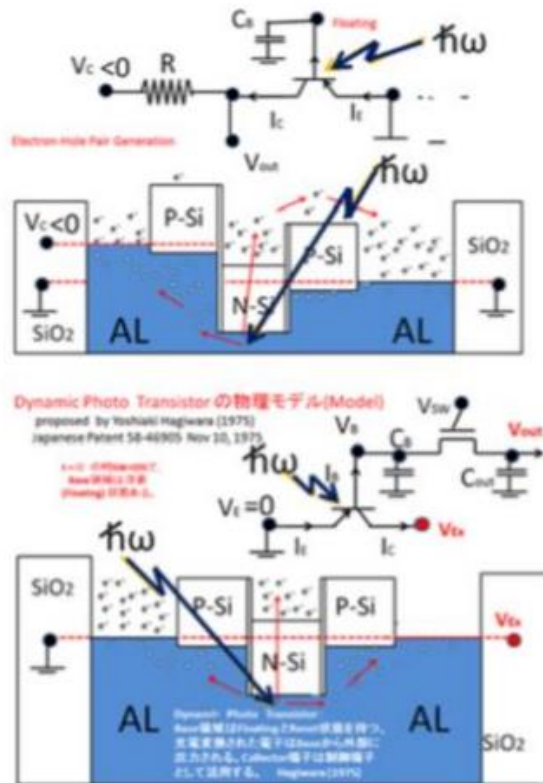




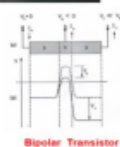
### Bipolar Transistor

Feynman Physics Volume III  
p.14-11 Fig.14-12

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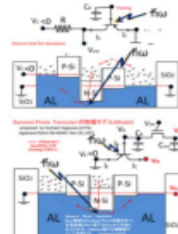


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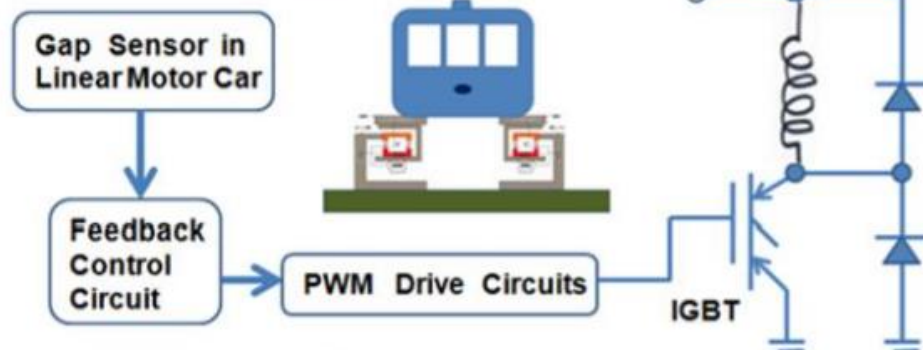
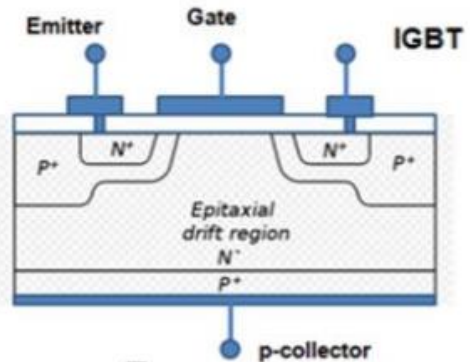
Bipolar Transistor

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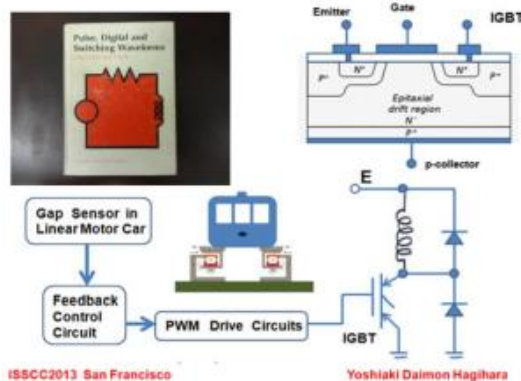
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(6) And this is a picture of an incoming photon incident to the bipolar transistor base region. The photon energy creates an electronhole pair and the photo-electron can be stored in the base as the majority carrier. So I see that a bipolar transistor can also function as a photon detector and/or a storage container. As you know, a room in a hotel must be empty and clean before the first hotel guest arrives. So must be this transistor base region empty and clean with no guest electrons this transistor base region empty and clean with no guest electrons at the beginning. In this way, I thought a transistor is useful since it can capture, confine and control one single electron. But I did not know yet how to move that single photo-electron in the base container to the outside terminal so that we can use it as a signal. That is, I had no way yet to know whether the guest has checked in the hotel and resting in the hotel room. I had no way yet to ask the hotel guest to come up to the hotel room. I had no way yet to ask the hotel guest to come up to the hotel lobby to meet me. I had to wait a few more years to find the answer. We all know now it is CCD, a charge coupled device that is a series of capacitance that can store and transfer one single electron. With a output circuit of a pre-charge reset set gate and a source-follower circuit we can finally meet our hotel guest at the hotel lobby !



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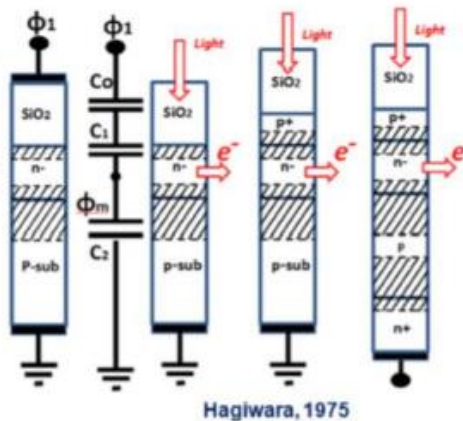
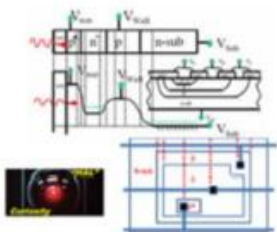
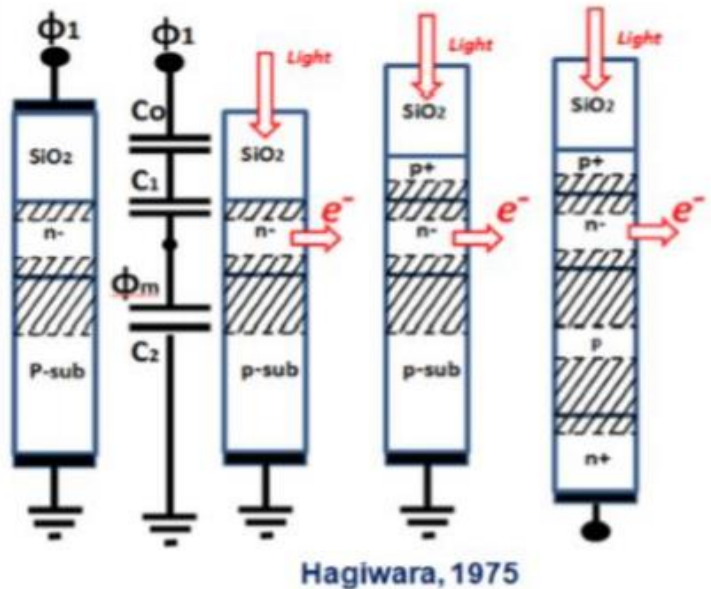
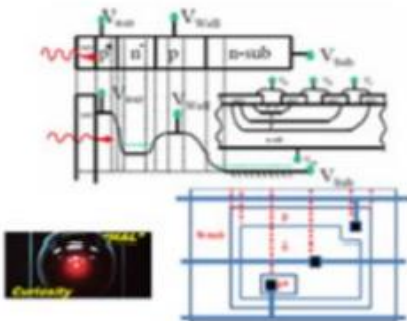
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(10) A slight modification of this p-n-p-n diode gives us another very useful device, which we call Insulated Gate Bipolar Transistor. This is a key device for a linear motor car of the future ! This is a simple inverter circuit with an inductance coil as the load element and the driving device is an Insulated Gate Bipolar Transistor with the PWM control input. The PWM, Pulse Width Modulation, technique is a very powerful and useful digital circuit system technique now universally applied for driving servo motors for many mechanical system applications including Robotics. This PWM circuit technique is useful to control the On-AND-OFF Digital current flow in the magnetic coil used to make a linear motor car to float and move in the air. make a linear motor car to float and move in the air. In a special dynamic operation mode, this device also works as a simple p-n-p-n capacitance that can detect one single electron . And it works as a key device element in modern imagers.



(16) But soon I found out this is no good for imaging. It has a metal layer on the top! The metal layer does not allow light to pass through.

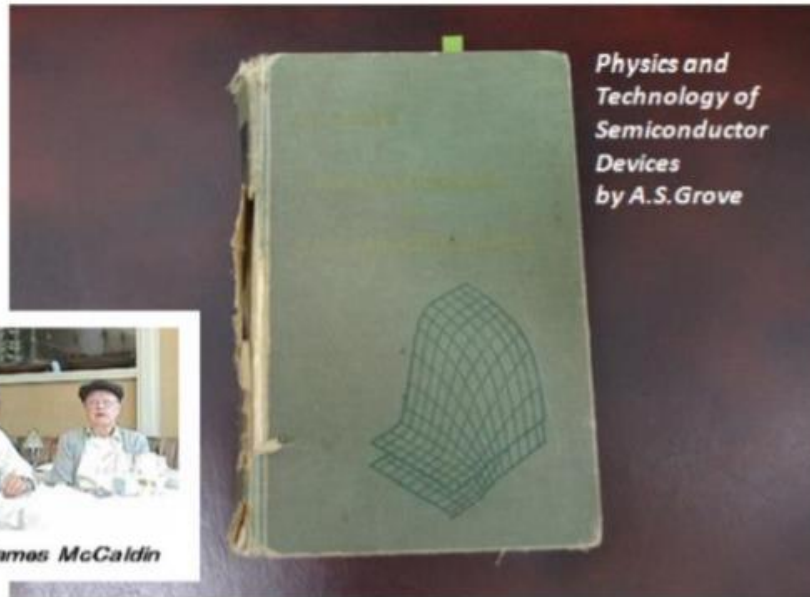
So we still needed the original photo-diode, the photo-transistor, and the p-n-p-n photo-diode that I had studied when I was an undergraduate student.

At least they can pass the light through the device and catch a single electron in the dynamic capacitance mode of their operations.





*Prof. James McCaldin*



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**Yoshiaki Daimon Hagihara**

(11) Then the third book I studied, with the guidance of Prof. John McCaldin, was "Physics and Technology of Semiconductor Devices" by Andy S. Grove.



*Prof. T. C. McGill*



*Prof. James McCaldin*

(13) When I was about to start my graduate work, I learned about a new device called CCD. I thought we now have a device to detect the arrival of the first guest electron in our empty hotel room !With this device I thought I could ask the guest electron to come up to the hotel lobby to meet us ! I was excited . I thought this is the device we were looking for, that can transfer one single electron in solid from one place to another and to the final output circuit stage. I was excited, and many people were also excited ! Many researchers worked on this device with great expectations. I worked on this device with great expectations. I was excited and worked on this device with the guidance of Prof. T.C. McGill .



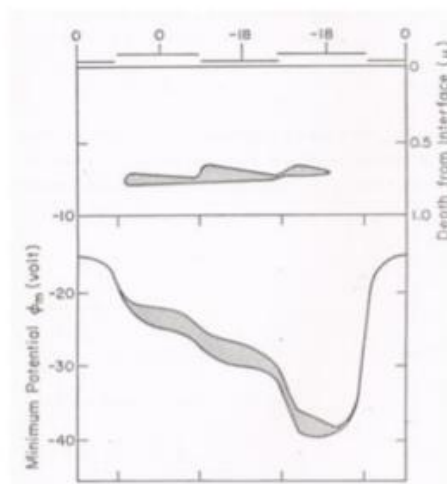
## Charge-Coupled Devices and Applications

Chairman  
Lewis M. Terman

Testimonial to the importance of the charge transfer phenomenon is attested to by the Morris N. Liebmann and the David A. Sarnoff awards this year to the originators of the charge-coupled and bucket brigade devices, respectively. The papers in this section concentrate on the former.

Charge-coupled devices are unique among semiconductor elements. In all other device embodiments into circuits, charge is manipulated and extracted and then used to charge a capacitor or passed through a resistor in such case to develop a signal voltage, to

My PhD thesis paper  
on buried channel CCD  
at ISSCC1974, in Philadelphia, USA



Prof. T. C. McGill



Prof. C. A. Mead

- (14) I became specially interested in a buried channel CCD structure since this device protects a single electron, our important hotel guest, from being trapped by the Si-SiO<sub>2</sub> interface states. . I analyzed how the electron charge move in the buried layer of BCCD structure by computer simulation, done at JPL Caltech Pasadena, with the guidance of Prof. T. C. McGill and Prof. C. A. Mead in Caltech. And, I published my PhD thesis work on buried channel CCD at ISSCC1974, in Philadelphia, USA

## Yoshiaki Higihara: The p-n-p-n Diode in Future Linear Motor Cars and in Modern Imagers

John Louis Moll (1921–2011) was studying a p-n-p-n diode switch in his Ph.D. dissertation work when the first ISSCC was held in 1954. In a normal operation mode, this device works as a thyristor, which can drive a large current and is the key device structure of an IGBT applied for a linear motor car of the future (see Figure 9). In a dynamic operation mode, this device may work as a simple p-n-p-n dynamic capacitance that can detect and store one single electron, which is a key device structure of the modern image sensor (see Figure 10).

I recall, when I was taking his physics course at Caltech, that Feynman once said that an electron is always free, moving around rapidly in free space, even in solid, and it never stops. It is very hard to catch an electron because we do not know exactly where it is. Our civilization today is based on a technology that controls electrons, down to a single one.

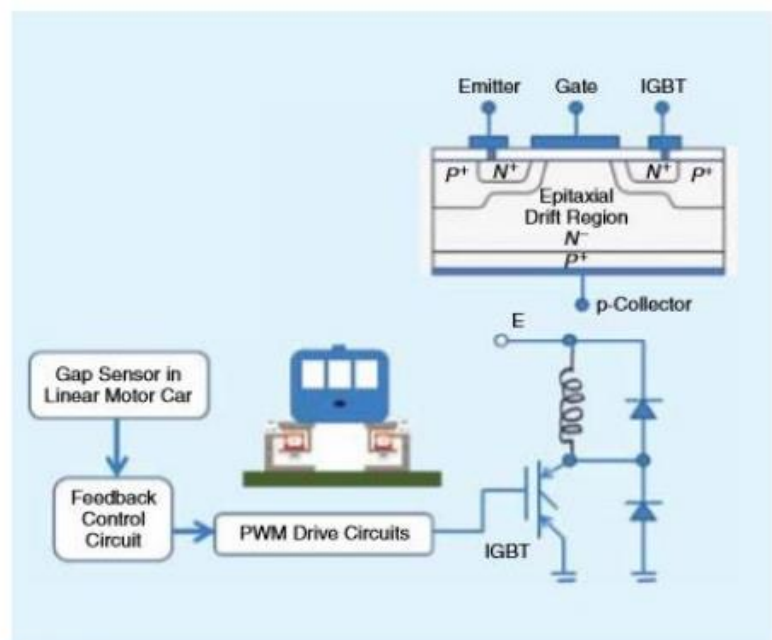


FIGURE 9: The p-n-p-n switch diode for a modern linear motor car.



Imagine a photon incident to a bipolar transistor base region. The photon energy creates an electron-hole pair. And the photo-electron can be stored in the base region as one single majority carrier. That is, a bipolar transistor can also function as a photon detector and/or a storage container. I thought that a room in a hotel must be empty and clean before the first hotel guest arrives. So must be this transistor base region empty and clean with no guest electrons at the beginning. This transistor in a dynamic p-n-p capacitor mode is useful since it can capture, confine, and control one single electron. But as a student, I did not know yet how to move that single photoelectron sitting in the base region to the outside world so that we can make use of it as a signal. I had no way yet to know whether the hotel guest has arrived and is resting in the hotel room or not. We had no way yet to ask the hotel guest to come up to the hotel lobby to meet me. I had to wait a few more years (until 1970

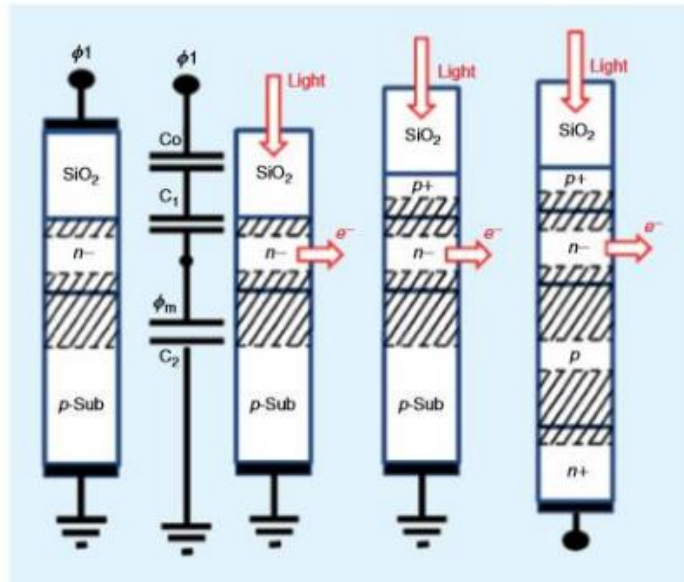


FIGURE 10: From CCD to the dynamic p-n-p-n diode capacitors.

in my senior year in college) to find the answer. We all know now it is the CCD structure that can store and transfer one single electron. With a precharge reset set gate and

With a precharge reset set gate and a source-follower circuit, a scheme invented by Walter Kosonocky. We could finally meet our hotel guest at the hotel lobby.

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Date of publication: XXXXX

## Antiques from the Innovations Attic

Rousing nostalgia for the IC yesteryear, panel organizers Trudy Stetzler, Bram Nauta, and Anantha Chandrakasan said in their Conference Digest overview "When you clean up your attic you may find things that you have totally forgotten about: old toys you used to play with, old books with lost stories. And then you think back to those past days and view them in the context of today's busy life, and sometimes find new uses for forgotten items. This panel does a similar thing."

The six experts they invited from academia and industry "to dig into their memories and find lost treasures in circuit design" were asked specifically "to reveal circuits and concepts that they feel are the most

interesting, intriguing, and under-appreciated innovations from the past" and to "explain why the concept is significant today and should be pulled from the innovation attic."

Their confab, which drew an estimated 2,000 people on Monday evening, offered many notable remembrances:

Eric Vittoz highlighted "current-mode analog circuits in weak conversion" as those seldom used in the past because of their poor precision due to threshold mismatch. But these circuits, he said, may regain

**Organizer:** Trudy Stetzler, Houston, Texas

**Moderators:** Anantha Chandrakasan, Massachusetts Institute of Technology, Cambridge, and Bram Nauta, University of Twente, Enschede, The Netherlands

interest in deep submicron processes where larger-than-minimum devices could be used to reduce threshold mismatch.

Coincidentally, Rinaldo Castello also highlighted current-based



From left: Thomas Lee, Nicky Lu, Rinaldo Castello, Yoshiaki Hagihara, Eric Vittoz, Robert Brodersen, and panel moderators Anantha Chandrakasan and Bram Nauta

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Nicky Lu, flanked by intently listening Tom Lee and Rinaldo Castello.



Yoshi Hagihara, Eric Vittoz and Bob Brodersen.

processing as the antique from the past with renewed appearance as what he termed "pipe" processing and "pipe" filters.

Robert Brodersen offered time-domain processing as his "basic attic idea" and how this could be

used to attack the most important problems of radio design. He pointed to impulse radio and active cancellation as "two time-domain projects from the attic."

Nicky Lu picked core memory as an antique that is now resurfacing

as spin-torque transfer magneto-resistive random-access memory (STT-MRAM).

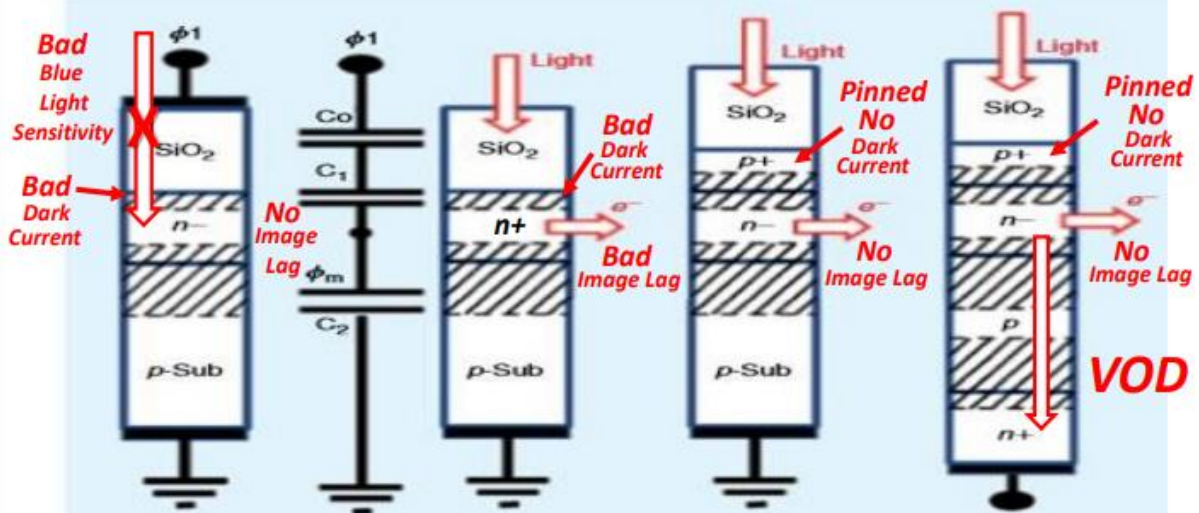
Yoshiaki Hagihara shared his memories of Richard Feynman, his mentor and educator at Caltech, and how he learned from him that control of electrons is at the heart of all electronic devices. As an example from his attic, he pointed to the old p-n-p-n junctions that are now incorporated in modern-day image sensors.

The last speaker of the session, Thomas Lee, focused on the mysteries and misunderstandings surrounding the linear time-varying (LTV) circuits where the Laplace transform in its simple form cannot be used for analysis. Examples from his attic were super-regenerative amplifiers and parametric systems.

A full-length accounting will appear in this magazine in the Summer 2013 issue.

—Ali Sheikholeslami  
ISSCC Educational Events Chair

## History of dynamic Solid State image sensing structure from BCCD type MOS capacitor to the P+NPN junction Pinned Photodiode capacitor



**(1) CCD type**

*invented by  
Bell Lab in 1968*

**(2) N+P type**

*The classical photodiode  
with serious image lag*

**(3) P+NP type (4) P+NPN type**

*(3) and (4) are the P+NP junction type Pinned  
Photodiode invented by Yoshiaki Hagihara, 1975*

*In Japanese patent 1975-134985, Hagihara at Sony invented the Pinned photodiode with very low dark current, which is also the completely depleted Buried Photodiode with image lag free picture quality, and also with the built-in vertical overflow drain ( VOD ) function.*

*Reference: IEEE Solid-STATE CIRCUITS MAGAZINE, SUMMER 2013 issue pp. 6 ~*