The invention of the transistor: revisiting the « magic month » through the prism of C/K design theory

Sylvain Lenfle – CNAM (LIRSA) et i3/CRG
Loïc Petitgirard – CNAM (HT2S)

Why the transistor ?

• December 16th, 1947 : demonstration of a working point-contact « transistor » at Bell Labs by J. Bardeen & W. Brattain
  – A technical breakthrough
  – Leading to « Junction transistor » (1948) …and others !
  – Opening the « Silicon Valley » and the « Information age »


• A very rich empirical material :
  – L. Hoddeson research program on the transistor (1981 – 1997)
  – W. Shockley reflection on the process (Shockley, 1974 & 1976)
The « magic month »  
(Shockley, 1974)

- A term coined by Shockley
- a « burst of creativity » at Bell Labs culminating with the Point-Contact transistor

**But :**
- Even in the paper : more than a month
- **Two different designs**
  - point-contact
  - junction transistor (feb. 1948)

How did they get to this revolution ?
⇒ **revisit the magic month through the prism of CK design theory** (Hatchuel & Weil, 2009) to understand the story and the design process behind the transistor
⇒ **emphasize the role of organization and time (long-term history) in the process**
The starting point: replacing vacuum tubes

- A research topic at Bell Labs supported by M. Kelly’s vision in the mid-30’s: replacing vacuum tubes (VT) function to function by a « semi-conductor amplifier ».
  - Well known weaknesses of VT: heating, power hungry, fragile, size…

- Initial approach: adapt the components of VT into semiconductor material (structure to structure)
  - Semiconductors = potential candidates to replace VT
  - 1st “naïve” concept: looking for a “semiconductor triode”, trying to insert a “grid” in a metal / semiconductor device (or two layers of semiconductor) = failure

K-base (K₀) – 1945

- A “rough” theoretical basis:
  - quantum theory of rectification (Mott-Shottky theory – for copper oxyde / concept of “majority carrier”)
  - quantum theory of metals / conduction

- W. Shockley (at Bell Labs since 1936) experiments on a semiconductor amplifier:
  - Structure to structure experiments (Brattain & al.) => failure
  - a “field-effect” amplifier in 1939 and april 1945 => only failures

- War Research effort on radar (rectification for radar)
  - new K on the metallurgy of SC in particular Silicon (Si) and Germanium (Ge)
  - Identification of « p-n junction » in Si.
The organization

- June 1945: creation of the Solid States Physics Department at Murray Hill led by W. Shockley & S. Morgan

- An original research strategy
  - A multidisciplinary approach directly inherited from WWII Rad Lab project
  - A case of "use-inspired basic research" (Stokes, 1997)
  - A very careful design of the physical environment to enhance communication between the actors involved

- Octobre 1945: J. Bardeen’s arrival at Bell Labs
  => 1st breakthrough in K

« It is frequently said that having a more-or-less specific practical goal in mind will degrade the quality of research. I do not believe that this is necessarily the case and to make my point in this lecture I have chosen my examples of the new physics of semiconductors from research projects which were very definitely motivated by practical considerations. » (W. Shockley Nobel Lecture, 1956).

=> "Respect for scientific aspects of practical problems" (1974)
Bardeen’s *surface state* hypothesis

Replace vacuum tubes by solid-state components

**System / ATT**

Use / ATT System / Demands of VT

**K₀**

Doesn’t work ⇒ Bardeen’s surface state hyp. (March 1946)

**Silicon**

Photovoltaic effect

**Electrolytes**

Magnetic effect

Systematic exploration of Electrolytes

**Germanium**
The magic month (17 nov. - 16 dec. 1947)

Replace vacuum tubes by solid-state components

- Field effect Tr
  - Silicon
  - Germanium
- Photovoltaic effect
- Electrolytes
- Magnetic effect

Systematic exploration of Electrolytes

Use / ATT System / Demands of VT

K₀

Bardeen’s surface state hyp.

Nov 17th, 1947 overcome the Surface state. Inversion layer.

Point contact + electrolyte

Point-contact (old technology)
The magic month (17 Nov. - 16 Dec. 1947)

Replace vacuum tubes by solid-state components

- Use / ATT System / Downsides of VT

- Amplification exist but weak

- Dec 8th, 1947 – discussion Shockley / Bardeen / Brattain:
  - Shockley propose p-n junction in electrolyte => new C – not followed
  - Bardeen proposes to use « high back voltage germanium » from Purdue University.

- Systematic exploration of Point contact solutions

- HBV Ge

- Point contact + electrolyte (Nov 21th)

- Point contact + Ge

- Systematic exploration of Point contact + Ge

- Field effect Tr

- Silicon

- Germanium

- High back voltage germanium

- Electrolyte (Nov 21th)
The magic month (17 nov. - 16 dec. 1947)

Replace vacuum tubes by solid-state components

- Field effect Tr
- Point contact + electrolyte (21/11)
  - Silicon
  - Systematic exploration of Point contact solutions
- Point contact + oxide
  - HBV Ge
  - Systematic exploration of Point contact + Ge

Use / ATT System / Weakness of VT

Amplification exist but weak

Dec 8th 1947
Bardeen's suggestion of high back voltage Ge

Accidentally
Layer of oxide instead of electrolyte!

16 dec. 1947
Gold + 1 Point-contact
Gold + 2 Point-contacts

Point-contact « transistor »

Bingo !!!
BUT HOW DOES IT WORKS?

NOTE THAT
BELL LABS
ALLOWS VERY
VERY FAST
ITERATIONS
The « point-contact transistor »  
(dec. 16, 1947)

Named « transistor » in may 1948

« Frankly Bardeens and Brattain’s point-contact transistor provoked conflicting emotions in me. My elation with the group’s success was balanced by not being one of the inventors. »

W. Shockley, 1974, p. 54.
Enter Shockley: the 2nd magic month
(31 dec. 47 – 23 jan. 1948)

Replace vacuum tubes by solid-state components

Point contact + electrolyte (21/11)
Point contact + oxide

Silicium

Systematic exploration of Point contact

Gold + 1 contact
Gold + 2 contact

Point-contact transistor, 16 dec. 1947

31/12/1947: Shockley’s concept of a n-p-n amplifier

23/01/1948: Shockley’s hypothesis on the role of minority carrier in the PtTr.

BREAKTHROUGH IN K => K-REORDERING

[Theory of the] Junction transistor with thin p-layer & minority carrier injection

Use / ATT System / Demands of VT
Enter Shockley: the 2nd magic month (31 dec. 47 – 23 jan. 1948)

Replace vacuum tubes by solid-state components

- Point contact + electrolyte (22/11)
- Silicon

Silicon

- Germanium

Germanium

- n-p-n junction amplifier

[Theory of the] Junction transistor with thin p-layer & minority carrier injection

垄断/ATT
System/Downsides of VT

J.N. Shire 19/2/1948
« double-surface transistor » experiment: first validation of the theory;
WS unveiled his theory to the SC group.

Point-contact transistor, 16 dec. 1947

Designing the transistors

- **Point contact transistor:**
  - A breakthrough without a theoretical understanding
  - Far from « structure to structure » replacement of VT
  - Creation of an exploratory development group
  - An industrial nightmare !!!

- **Junction transistor**
  - Start as a purely theoretical device
  - 2 years of R&D: working April, 12, 1950 / Announced summer, 1951.
    - In particular on the metallurgy of germanium: « good p-n junction prepared by sparks & teal by changing the doping of the melt in germanium crystal grower by « pill dropping » and subsequent double doping to make n-p-n structures » (in Shockley, 1976)
  - Publication of Shockley’s classic *Electron and holes in semiconductors with application to transistor electronics* (nov. 1950) => Complete re-ordering of the K-base ~ bible of the Silicon Valley
Epilogue (1)

- Shockley leaves Bell Labs in 1955 to create *Shockley Semiconductor Laboratory* => roots of the Silicon Valley

- The Junction Transistor will not « replace » vacuum tubes before years.
  - 1st important application = Minuteman ICBM
  - Portable radios / hearing aids…
  - and, in the late 1950s : computers
    => Essentially : miniature device + new uses !!
    => Neither « structure to structure » nor « function to function »

- Nobel Prize in physics for SBB in 1956.

Nobel celebration at Shockley Lab, 1956
Epilogue (2)

- The *magic month* is only the tip of the iceberg

- Unveiled the creation process of a new K-base and the ensuing massive K-reordering (Hatchuel & al., 2015; Le Masson & al., 2017)
  - New theoretical basis: quantum physics
  - A ten years long process (including WWII)
  - Supported by M. Kelly’s initial vision…
  - … and Bell Labs multi-disciplinary approach to research.
  - A complex process interlacing theoretical hypothesis, experimentation, working-but-why devices, calculations, insights and creative discussions between high-level scientists.

- New K-base proved to be extremely generative: incredible expansion in C and birth of the information age / Silicon Valley
Shockley Lab
and the growth of the Silicon Valley

Fairchild Semiconductor (1957)

AMD (1969)

Intel (1968)

Shockley Lab. (1955-56)

sylvain.lenfle@lecnam.net
loic.petitgirard@lecnam.net