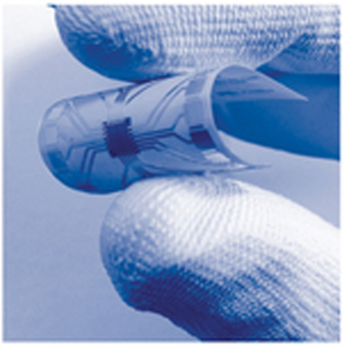
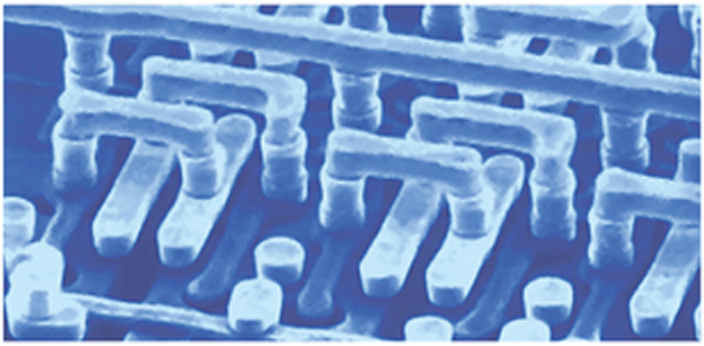
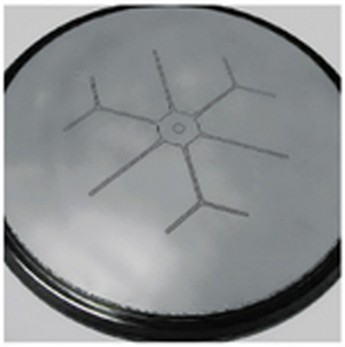





Guide to State-of-the-Art Electron Devices

Editor Joachim N. Burghartz



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GUIDE TO STATE-OF-THE-ART ELECTRON DEVICES

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Edited by

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Contents

Foreword

No one can ever doubt that electronic devices provide the basis of the way large components of our civilization operate today. This book refreshingly provides both a well-organized history and state of the art of the many technologies involved, how they are connected and most importantly, how this evolution (and frequently revolution) took place. I am overjoyed to see that the IEEE Electron Device Society has taken on this challenging undertaking and succeeded so well. The editor has made excellent choices of authors to cover such a daunting challenge. I have known many of them personally and can attest to that claim.

The initiation of the EDS and its growth has coincided with this revolution and it has been the principal organization in creating conferences and providing publications in which people can present results and interact with others working in their field. The importance of this cannot be overemphasized since the trading of ideas, not to mention competition, between people in a field provides fertilizer for new ideas. Incidentally, it is not too much of an exaggeration to say that, at conferences, as much information has been traded in the hallways as in the technical sessions. The inception of this book is a continuation of that fine tradition of publicizing information.

Although each chapter in this book covers a separate subject, they all start with a historical and tutorial mix before attacking the current state of the art. This is very beneficial to both students and experts in a given field who wish to broaden their horizons. I especially applaud the use of the blue sidebars which explain terms and concepts which require no explanation for those in the field but are enigmas to those less knowledgeable.

George E. Smith

Note: Dr. George E. Smith received the 2009 Nobel Prize in Physics for ”the invention of an imaging semiconductor circuit – the CCD sensor”. He is also a Celebrated Member of the IEEE Electron Devices Society.

Foreword

This book marks the 35th anniversary of the IEEE Electron Devices Society (EDS), a journey that began with the formation of the IRE Professional Group on Electron Devices 60 years ago. The major technical advancements in the field of Electron Devices are commemorated chronologically through the "video clips" at the bottom of the pages throughout the book. These clips represent snapshots of many pioneers whose aspirations and dedication led to the discovery of numerous device concepts and their implementation into practical use. This historical time line links well to the electronic booklet "50 Years of Electron Devices," which is freely available on the EDS web site.

Although the invention and development of vacuum tube devices for communications and sensing predated the age of transistor, it was the advent of the solid-state "triode" in 1947, followed by the integrated circuits in the late 1950s, that has ceaselessly pushed new frontiers in computers, communications, and many other emerging areas in the several recent decades. The work described in this book has revolutionized the way we live and the way we think. As the continuous, insatiable demand for higher performing electronics drives the search for new materials and devices, the global electron devices community will again and again respond to new challenges with novel solutions.

This book was compiled from contributions from many volunteer leaders of the Society. It is our sincere wish that its technical content will serve as a bridge between the last sexagenary cycle and the next.

Paul Yu
IEEE EDS President 2012–2013

Preface

Electronics and power electronics have grown to be indispensable technologies supporting our lifestyle, our health and our safety, social interaction and security. None of today's industries would be viable without electronic communication, automation and control. Through electronics people stay connected, get supported in their professional life, and can enjoy leisure entertainment. Transportation and energy supply depend on electronics as well. Electron devices are the foundation of electronics and power electronics. They enable all kinds of electronic signal processing and allow for switching and steering electrical energy.

This book features a concise guide to state-of-the-art electron devices. It is written by 67 specialists who are members of the IEEE Electron Devices Society (EDS). In 21 chapters they share their expert view on a particular group of electron devices or device aspects. The chapters not only illustrate the broad variety of electron device and device aspects but they are also a mirror of the diversity within the EDS. There are contributions from industry, academic and government institutions. Authors come from all five continents – a true world class team which includes the top-level industry manager as well as young engineer, the renowned university professor, and the young academic. The editor therefore tried to keep the apparent differences in style and language intact to reflect the rich diversity in regional background and affiliation.

Most of the authors are members of one of the 14 Technical Area Committees (TACs) in EDS, which assist the Executive Committee (ExCom) and Board of Governors (BoG) of EDS with their expertise in decision making and strategy processes. The current TACs in EDS are listed in Table 1.

The Institute of Electrical and Electronics Engineers (IEEE), the world's largest professional association, has its roots in the American Institute of Electrical Engineers (AIEE; founded 1884) and the Institute of Radio Engineers (IRE; founded 1912), which merged in 1963 to form the IEEE. The IRE already paid attention to the significance of electron devices by establishing an 'Electron Tube and Solid-State Devices Committee' in 1951 shortly after the invention of the transistor. In 1952 the committee's name was changed to 'IRE Professional Group on Electron Devices'. With the merger of AIEE and IRE an 'IEEE Electron Devices Group' was established in 1964, which in 1976 became the 'IEEE Electron Devices Society (EDS)'.

Today, we look back at the 35-year history of the IEEE Electron Devices Society and at its foundation in the IRE 60 years ago: two great reasons to celebrate and provide the members and potential new members of EDS with this concise guide to state-of-the-art electron devices at a very affordable price. This was made possible by substantial sponsorship through EDS and by dedicated volunteer contributions.

Table 1 Technical Area Committees of the IEEE Electron Devices Society

Compact Modeling	CM
Compound Semiconductor Devices and Circuits	CSDC
Device Reliability Physics	DRP
Electronics Materials	EM
Microelectromechanical Systems	MEMS
Nanotechnology	NT
Optoelectronic Devices	OD
Organic Electronics	OE
Photovoltaic Devices	PD
Power Devices and ICs	PDIC
Semiconductor Manufacturing	SM
Technology Computer Aided Design	TCAD
Vacuum Devices VLSI Technology and Circuits	VLSI

The book is organized in three parts, of which Part II (5 chapters) and Part III (11 chapters) are closely aligned with the TACs of EDS (see Figure 1). Part I of the book introduces in five chapters the fundamentals of electron devices. Sidebars are used in all chapters to define important figures-of-merit or definitions for a particular electron device and to offer an easy entry into the topic to the novice.

		PART III								
		CSDC (Chapter 14)	**MEMS** (Chapter 18)	**NT** (Chapter 21)	**OD** (Chapter 17)	**OE** (Chapter 20)	**PD** (Chapter 16)	**PDIC** (Chapter 15)	**VD** (Chapter 19)	**VLSI** (Chapter 11-13)
PART II	**CM** (Chapter 7)	●●	●●	●●	●●	●●	●	●	●	●●●
	DRP (Chapter 9)	●●	●●	●	●●●	●●	●●●	●●●	●●	●●●
	EM (Chapter 6)	●●●	●●	●●●	●●	●●●	●●	●●	●●	●●●
	SM (Chapter 10)	●●	●●	●	●●●	●	●●●	●●●	●●	●●●
	TCAD (Chapter 8)	●●	●●●	●	●●	●	●●	●●●	●	●●●

Figure 1 Relationship of the Technical Area Committees in the IEEE Electron Devices Society and their organization in Parts II and III of the book

A highlight of the book is the comprehensive timeline at the page bottom, featuring the historical milestones of electron devices in chronological order in three eras, after 1976, between 1952 and 1976, and before 1952. These eras mark the time periods of EDS, of electron devices in the IRE prior to EDS, and of the early electron devices, respectively.

Besides the actual contributors many people have helped ‘behind the scenes’ to turn the idea of this anniversary book into reality. They are duly acknowledged in the *Acknowledgments* section.

Joachim N. Burghartz

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The editor, on behalf of all contributors, considers it a great honor that this book is introduced by a foreword of **Nobel Laureate George E. Smith**. His kind words helped us to complete this ambitious project.

Joachim Deh from IMS CHIPS in Stuttgart helped with editing some of those and other images used in the timeline and in Chapter 4 and with arranging copyright permissions for such images. **Fernando Guarin** (EDS Secretary) carried out a critical review of parts of the book prior to the copyediting by the publisher. **Peter Mitchell, Laura Bell, Liz Wingett, Richard Davies,** and **Genna Manaog** from John Wiley & Sons as well as **Sangeetha Parthasarathy** from Laserwords Pvt Ltd. are acknowledged for arranging a smooth copyediting and publication process; particular thanks goes to **Peter Mitchell** for his patience in negotiating the terms of the publication contracts. Advance acknowledgments go to **Bin Zhao** (EDS Vice President Meetings), **Xing Zhou** (EDS Vice President Regions & Chapters), **Jean Bae** (EDS Executive Office), again **Chris Jannuzzi**, and all organizers of EDS-sponsored meetings and EDS chapter chairs involved in distributing the book within the EDS community.

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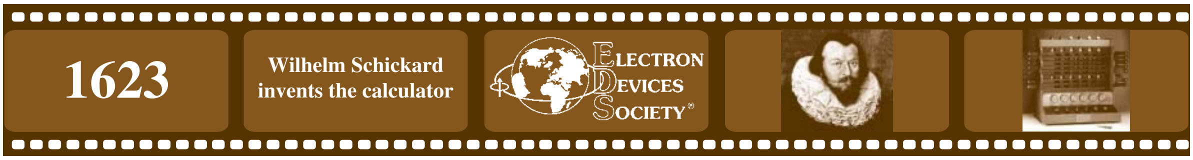
Introduction: Historic Timeline

Electron devices go back a long time: from the vacuum tube to the inventions of the transistor and the integrated circuit, through 40 years of scaling microelectronics to the exciting possibilities brought about by the current investigations on emerging research devices. The history of electron device applications is also captured here. Looking back in time means learning from the past so that future progress can be made more efficiently. It also means taking pride in the pioneers' achievement and viewing them as role models empowering young electron device engineers.

The historic timeline that runs as a movie strip at the bottom of the pages in chronological order through this entire anniversary book marks key milestones of electron device development and applications in more than 1000 slides. Landmarks of world history and other technical breakthroughs place those milestones into historical perspective. The book can, thus, be read in two ways; chapter-by-chapter, or along the timeline of device history.

Part I

BASIC ELECTRON DEVICES



Chapter 1

Bipolar Transistors

John D. Cressler and Katsuyoshi Washio

1.1 Motivation

In terms of its influence on the development of modern technology and hence, global civilization, the invention of the point contact transistor on December 23, 1947 at Bell Labs in New Jersey by Bardeen and Brattain was by any reckoning a watershed moment in human history [1]. The device we know today as a bipolar junction transistor was demonstrated four years later in 1951 by Shockley and co-workers [2] setting the stage for the transistor revolution. Our world has changed profoundly as a result [3].

Interestingly, there are actually seven major families of semiconductor devices (only one of which includes transistors!), 74 basic classes of devices within those seven families, and another 130 derivative types of devices from those 74 basic classes (Figure 1.1) [4]. Here we focus only on three basic devices: (1) the *pn* homojunction junction diode (or *pn* junction or diode), (2) the homojunction bipolar junction transistor (or BJT), and (3) the special variant of the BJT called the silicon-germanium heterojunction bipolar transistor (or SiGe HBT). As we will see, diodes are useful in their own right, but also are the functional building block of all transistors.

Surprisingly, all semiconductor devices can be built from a remarkably small set of materials building blocks (Figure 1.2), including [4]:

- the metal–semiconductor interface (e.g., Pt/Si; a "Schottky barrier")
- the doping transition (e.g., a Si *p*-type to *n*-type doping transition; the *pn* junction)
- the heterojunction (e.g., *n*-AlGaAs/*p*-GaAs)
- the semiconductor/insulator interface (e.g., Si/SiO_2)
- the insulator/metal interface (e.g., SiO_2/Al).

Guide to State-of-the-Art Electron Devices, First Edition. Edited by Joachim N. Burghartz.

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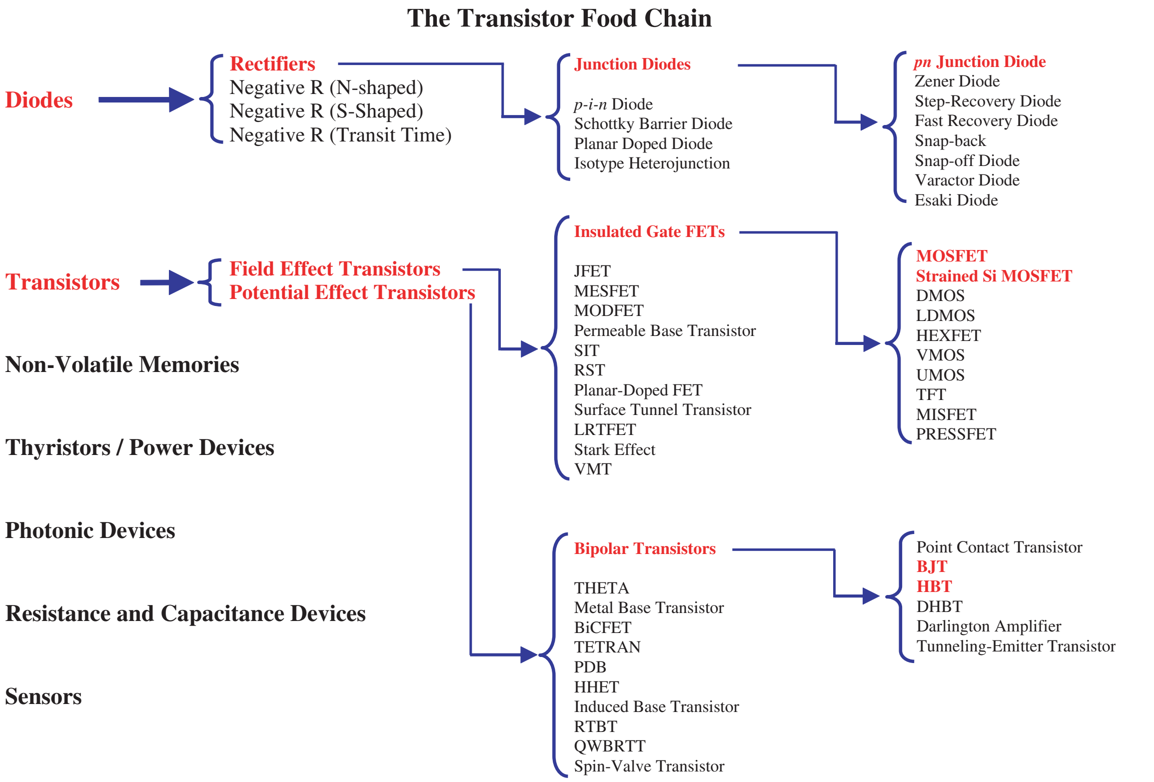
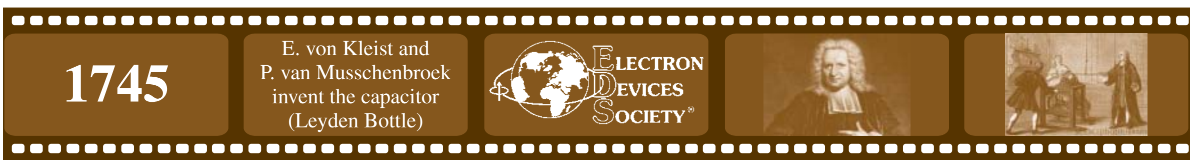


Figure 1.1 The transistor ''food chain'' showing all major families of semiconductor devices. Reproduced with permission from Cressler, J. D.; *Silicon Earth: Introduction to the Microelectronics and Nanotechnology Revolution*; 2009, Cambridge University Press

Why do we actually need transistors in the first place? Basically, because nature attenuates all electrical signals. By this we mean that the magnitude of all electrical signals (think "1s" and "0s" inside a computer, or an EM radio signal from a cell phone) necessarily decreases as it moves from point A to point B, something we call "loss". When we present an (attenuated) input signal to the transistor, the transistor is capable of creating an output signal of larger magnitude (i.e., "gain"), and hence the transistor serves as a "gain block" to "regenerate" (recover) the attenuated signal in question, an essential concept for electronics. In the electronics world, when the transistor is used as a source of signal gain, we refer to it as an "amplifier." Amplifiers are ubiquitous to all electronic systems.

Naming of the Transistor

The name "transistor" was actually coined by J.R. Pierce of Bell Labs, following an office betting pool which he won. He started with a literal description of what the device actually does electronically, a "transresistance amplifier," which he first shortened to "trans-resistor," and then finally "transistor" [3].



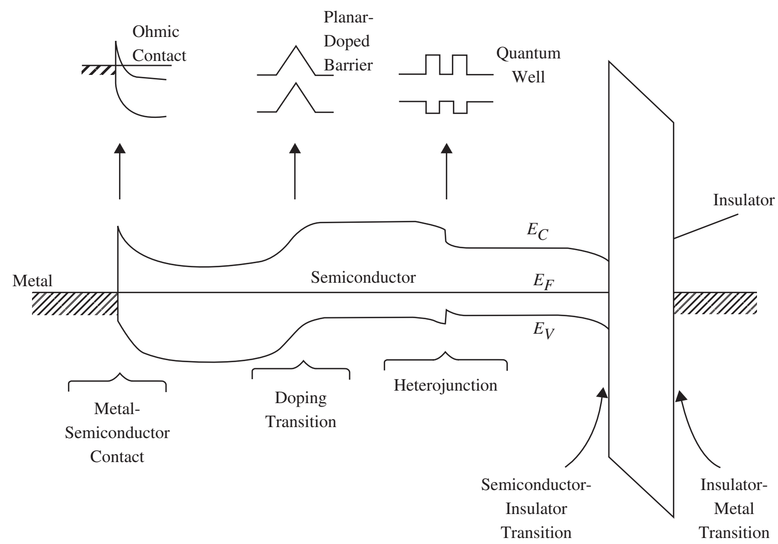


Figure 1.2 The essential building blocks of all semiconductor devices. Reproduced with permission from Cressler, J. D.; *Silicon Earth: Introduction to the Microelectronics and Nanotechnology Revolution*; 2009, Cambridge University Press

Not only can the transistor serve as a wonderful nanoscale sized amplifier, but importantly it can also be used as a tiny "regenerative switch"; meaning, an on/off switch that does NOT have loss associated with it. Why is this so important? Well, imagine that the computational path through a microprocessor requires 1 000 000 binary switches (think light switch on the wall – on/off, on/off) to implement the complex digital binary logic of a given computation. If each of those switches even contributes a tiny amount of loss (which it inevitably will), multiplying that tiny loss by 1 000 000 adds up to unacceptably large system loss. That is, if we push a logical "1" or "0" in, it rapidly will get so small during the computation that it gets lost in the background noise. If, however, we implement our binary switches with gain-enabled transistors, then each switch is effectively regenerative, and we can now propagate the signals through the millions of requisite logic gates without excessive loss, maintaining their magnitude above the background noise level.

In short, the transistor can serve in one of two fundamental capacities: (1) an amplifier or (2) a regenerative switch. Amplifiers and regenerative switches work well only because the transistor has the ability to produce gain. So a logical question becomes, where does transistor gain come from? To answer this, first we need to understand *pn* junctions.

1.2 The *pn* Junction and its Electronic Applications

Virtually all semiconductor devices (both electronic and photonic) rely on *pn* junctions (a.k.a., "diodes", a name which harkens back to a vacuum tube legacy) for their functionality. The simplest embodiment of a *pn* junction is the *pn* "homojunction", meaning that within a single piece of semiconductor (e.g., silicon – Si) we have a transition between p-type doping and n-type doping (e.g., p-Si/n-Si). The opposite would be

1750 | 1775 | ELECTRON DEVICES SOCIETY | 1782 | Alesandro Volta develops the condenser

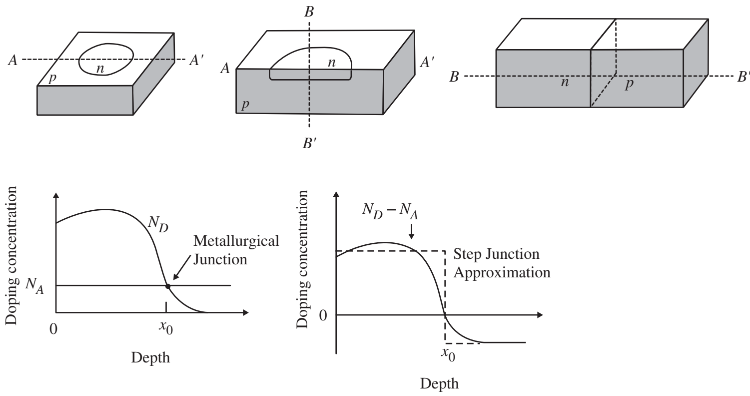


Figure 1.3 Cartoons of a pn junction, showing doping transition from n-type to p-type. Reproduced with permission from Cressler, J. D.; *Silicon Earth: Introduction to the Microelectronics and Nanotechnology Revolution*; 2009, Cambridge University Press

a *pn* heterojunction, in which the p-type doping is within one type of semiconductor (e.g., p-GaAs), and the n-type doping is within another type of semiconductor (e.g., n-AlGaAs).

As shown in Figure 1.3, to build a *pn* junction we might, for instance, ion implant and then diffuse *n*-type doping into a *p*-type wafer. The important thing is the resultant "doping profile" as one moves through the junction ($N_D(x) - N_A(x)$, which is just the net doping concentration). At some point in the doping transition, $N_D = N_A$, and we thus have a transition between net n-type and net p-type doping. This point is called the "metallurgical junction" (x_0 in Figure 1.3) and all of the important electrical action of the junction is centered here. To make the physics easier, two simplifications are typically made: (1) Let us assume a "step junction" approximation to the real *pn* junction doping profile, which is just what it says, an abrupt change (a step) in doping occurring at the metallurgical junction (Figure 1.3). (2) Let us assume that all of the dopant impurities are ionized (one donor atom equals one electron, etc., an excellent approximation for common dopants in silicon at 300 K).

So, how does a *pn* junction actually work? The operation of ALL semiconductor devices is best understood at an intuitive level by considering the energy band diagram, which plots electron and hole energy as a function of position as we move physically through a device. An n-type semiconductor is electron rich (i.e., majority carriers), and hole poor (i.e., minority carriers). Conversely, a p-type semiconductor is hole-rich and electron-poor. If we imagine bringing an n-type and p-type semiconductor into "intimate electrical contact" where they can freely exchange electrons and/or holes from *n* to *p* and *p* to *n*, the final equilibrium band diagram shown in Figure 1.4 will result. Note, that under equilibrium conditions, there is no NET current flow across the junction.

We might logically wonder what actually happened inside the junction to establish this equilibrium condition. When brought into contact, the *n*-type side of the junction is electron rich, while the *p*-type side is electron poor. That is, there is a large driving force for electrons to diffuse from the *n* region to the *p* region. Recall, that there are in fact two ways to move charge in a semiconductor: (1) drift, whose driving force is the electric field (voltage/length), and (2) diffusion, whose driving force is the carrier density gradient (change in carrier density per unit distance). The latter process is what is operative here.

1799

The first battery was demonstrated by Alessandro Volta

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