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A. VAPAILLE *editors*

INSTABILITIES IN SILICON DEVICES

Silicon Passivation and Related Instabilities

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INSTABILITIES IN SILICON DEVICES
Silicon Passivation and Related Instabilities

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INSTABILITIES IN SILICON DEVICES

Silicon Passivation and Related Instabilities

«La difficulté de réussir ne fait qu'ajouter à la nécessité d'entreprendre»

Figaro (Le Barbier de Séville - Acte I, Scène 6)

BEAUMARCHAIS

*This project was made possible thanks to the encouragement,
the logistical support and the financial help of
the IC manufacturing plant of Corbeil Essonnes,
of the IBM FRANCE Cie.*

THE EDITORS

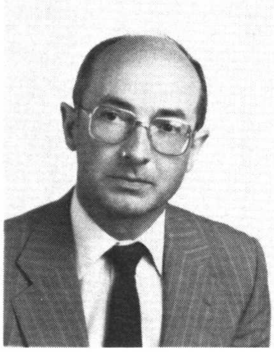
Gérard BARBOTTIN was born in Orléans (Fr.) in 1946. He graduated from the **Institut National des Sciences Appliquées de Lyon** (Fr.) in 1969.

He studied at the **Northwestern University** (III-USA), in the Technological Institute, from 1971 to 1973. He was awarded an **M.S.** degree from the Materials Science department for pioneering experimental work he carried out with **Dr. J. Hilliard** on composition-modulated thin films of binary alloys.

He joined Texas Instruments in 1974. He worked first as a process and process- control engineer in the IC assembly plant of Porto (Portugal) and after 1977 as a failure analyst and reliability specialist for Texas Instruments France in Nice (Fr.).

He joined IBM France in 1979 and has been since that date working at the laboratory of Physical Analysis of the IC manufacturing plant of Corbeil (Fr.). His only research goal has been to understand the physics of instability phenomena in silicon devices.

In 1980 he initiated, and has coordinated since then, the ambitious european scientific effort which lead to the writing of this book. After 1981 he received the support and cooperation of **Pr. Vapaille** with whom he reviewed and edited the texts of the book.



André VAPAILLE was born in St-Leu-la-Forêt (Fr.) in 1933. He graduated from the **University of Paris** in 1955.

He first carried out research work with **Pr Grivet** in the Electronics department of the University of Paris from 1958 to 1966. He was awarded the degree of «**Docteur d'état**» from the **University of Orsay**, in 1966 for his work on the deep levels of the silicon band gap introduced by irradiation and by impurities.

From 1966 to 1972 he pursued research work with R. Castagné on the interface states of the silicon-silicon dioxide structure and on impurity-related deep levels in silicon.

Since 1972 his research work has focused on the metal - semiconductor structure (Si and 3-5 compounds) as well as on epitaxial growth in high vacuum (after 1980). He teaches at the Institut Universitaire de Technologie belonging to the University of Orsay since 1972 and heads the Département de Mesures Physiques of that institute since 1980.

He has, for the past six years, lectured on device physics at the IBM manufacturing plant of Corbeil (Fr.).

FOREWORD

Today, silicon technology forms the basis of an $ 18 billion worldwide component industry. The reasons of this expansion can be found not only in the physical properties of silicon but even more so in the unique properties of the silicon-silicon dioxide interface. I say this because there exist other semiconductors which have a more appropriate band gap, which allow higher carrier mobilities or which possess physical parameters more suited to specific device applications. However none of the competing semiconductors can match the success of silicon mainly because they suffer from high surface recombination velocity and from surface instabilities.

Apart from its passivating properties, silicon dioxide possesses other technological advantages. Let us just mention here the ease with which it can be patterned by photolithography and its masking effect against diffusion.

Even though this book adresses the instabilities related to the passivation of silicon by silicon dioxide, it should be emphasized that the Si-SiO_2 interface is an unusually stable one provided certain precautions are taken during fabrication. Although these advantages are taken for granted today, lengthy technological developments were necessary to reach the present state of the art.

Having followed the history of the Si-SiO_2 technology from a very early stage, I would like to briefly outline the early problems which were encountered and how they were solved. In the beginning, the scientific investigation of semiconductor surfaces had only been performed on bare surfaces prepared under stringent conditions, in high vacuum. Experiments on surfaces oxidized, or chemically-treated, in air yielded unreliable results and lacked reproducibility. This was considered to be the result of «dirt effects». The experiments using cleaned surfaces in high vacuum showed that silicon and germanium had a very high surface states density which was at the time interpreted in terms of single level states.

The first device-oriented work on oxidized silicon surfaces came out of the Bell laboratories. It displayed a relatively low surface states density but still lacked repeatability and characteristics were unstable. Work was then initiated in several laboratories to develop the MOS field effect transistor which so far had only existed as a theoretical concept. Soon it was discovered that, in addition to surface states, positive charges were also present at the interface. The positive charges were identified as being the main cause of device instability. It took many years of work by the technologists (and many heated discussions) before alkali ions were identified *as the culprits. Simultaneously, techniques to stabilize the interface were developed: let us mention here the use of phosphorus glass and the introduction of process improvements to reduce the amount of active alkali ions.*

After stable interfaces were achieved, the door was opened to a better scientific understanding of them. MOS capacitors could be prepared very easily and yielded a wealth of information about interfaces and interface states. It was recognized that the interface states were continuously distributed across the forbidden gap and that unavoidable density fluctuations of positive charges resulted in potential fluctuations at the interface. Following this, it was possible to further the knowledge about other types of instabilities, e.g. those caused by electronic processes like carrier injection and those due to irradiations.

In spite of the instabilities it displays, I would like to emphasize once more that the Si-SiO_2 *interface is the most stable and the most controllable interface known today.*

This book, the result of a fruitful european cooperation, gives a highly desirable and up-to-date review of the physics of instability phenomena. It studies their fundamentals, shows how they affect silicon-based devices and gives the reader ways to study and to overcome them.

Adolf Goetzberger

A WORD FROM THE EDITORS

The sucess of silicon

Silicon is by far the most widely used semiconductor material in fabricating both discrete and integrated electronic devices. One of the main reasons behind this success stems from the outstanding qualities of silicon dioxide which can be used as a passivating layer as well as a gate insulator. However, and in spite of steady improvements in fabrication processes, silicon devices are still subject to unwanted electrical phenomena referred to as **instabilities.**

Unstable versus permanently defective devices

One of the most baffling problems faced by engineers in the silicon industry and users of electronic devices is that of **unstable** devices. These differ from permanently defective devices in a somewhat subtle way.

A permanently defective device displays electrical characteristics which are irreversibly «off-specification». This behaviour is almost always due to clear-cut defects in the silicon substrate or in the metal layers. Such a device can be easily screened out by electrical testing.

A device is called unstable when at least one of its electrical characteristics drifts in an impredictable manner during normal operation (in the field). It is thus difficult to eliminate by previous electrical testing and represents a threat to quality and reliability.

By extension a device will also be called unstable if, when subjected to an **«accelerating stress»** one of its characteristics drifts abnormally during stress and/or fails to return to its former value once stress has ceased. The word stress encompasses not only heating (usually below 400°C), bias and irradiations but also aging (alone or combined with the other three).

Instabilities and the «charge» problem

A drifting characteristic can almost always be linked to the motion of **charges** (ions or carriers) in an insulating layer of the device. This, in the past, lead specialists to refer to the problem of instabilities as the «charge problem». This problem was at the time often associated with the contamination of silica layers by sodium atoms. Nowadays other causes have become just as important : hot carrier injection, carrier trapping and detrapping, charge and discharge of interface states, radiation damage, etc...

Practically all instabilities stem from the fact that the dielectrics used to manufacture silicon devices are neither perfect electrical insulators nor perfect chemical passivators and that the silica network matches imperfectly the silicon lattice.

Instabilities and new trends in microelectronics

Most instability phenomena have been studied for years but are of renewed interest because of new trends in microelectronics : greater device integration subjects passivation layers and gate oxides to ever-increasing thermal and electrical stresses. Silicon devices are more frequently used in hostile environments (military, nuclear, spatial). Finally «agressive» new fabrication processes (e.g. ion implantation, electrolithography, plasmas, etc...) substitute traditional ones and introduce new sources of instabilities.

Previous studies on instabilities

Silicon passivation and related instability phenomena have been the topic of countless studies over the last 25 years, and have inspired numerous congresses and symposia [1,2]. However, the sheer number of publications and proceedings is so overwhelmingly large that it can discourage the most ambitious reader.

Several review papers [3 - 13] have attempted to give an overall view of these phenomena but were of limited practical use. Some aspects of these phenomena have also been treated in several books [14 - 17] and a full monograph has even been devoted to «Instabilities in MOS Devices» by J.R. Davis in 1981 [18].

Scope of the present project

We believe that there is an urgent need for a didactic and up-to-date manual aimed at specialists and students in the field, and in which instabilities would be envisaged from the dual point of view of materials science and electronics. This book should help circuit manufacturers and circuit users alike to relate unstable electrical parameters and characteristics to the physical defects and impurities which caused them.

Audience

The topics treated in this manual are easily accessible provided the reader is familiar with the basics of materials physics and electronics. It should prove useful to :

- engineers and technicians working in the semiconductor industry in such fields as : circuit design, manufacturing engineering, material and process characterization, quality and reliability assurance, failure analysis,
- graduate students and research scientists in materials science and electrical engineering, interested in insulator physics, semiconductor physics, device physics and electronics.

Contents

This 1000- page study is divided into 6 parts and subdivided into 18 chapters.

Part I deals with the physics of silicon passivation from the point of view of materials science. It encompasses growth and deposition of silica layers on silicon with a special emphasis on thermal oxides. It looks at the imperfections of vitreous silica and at the impurities it contains. It also describes some often overlooked after-effects of silicon passivation, namely those taking place in the silicon substrate itself.

In Part II we look at the general electrical aspects of the MIS structure. We oppose ideal and actual MOS structures and see how any deviation from ideality affects the C(V) curve. We examine the complex nature of electronic conduction in thin insulators and see how and why large electric fields lead to oxide breakdown. We finally render the reader familiar with the concept of electric noise and with its applications to surface noise.

We review the electrical phenomena occuring in the bulk of silicon oxide in Part III. We re-examine the perennial problem of mobile ions which, in spite of process improvements, remains a potential threat to bipolar and MOS processes alike. We look at the many aspects of hot carrier injection into silicon dioxide and to the associated phenomena : carrier trapping and detrapping.

In Part IV we take a look at the electrical phenomena taking place at the $Si\text{-}SiO_2$ interface. Imperfections give rise to so-called intrinsic surface states, whereas impurities in the interfacial zone generate extrinsic surface states. We examine their properties, their impact on classic electrical characteristics and the models currently proposed to explain their origin. We review the techniques used to measure them and how these can be used for diagnostic purposes.

Practical examples of passivation-related instabilities in silicon devices are reviewed in Part V. Since the basic physics of instability phenomena has been seen in the earlier parts, these chapters should give the engineer quick ways of solving practical instability problems encountered on MOS and bipolar products. The peculiarities of structures possessing a double insulating layer are examined and their application to MNOS non-volatile memory cells detailed.

We end this book by surveying, in Part VI, the effects of radiation on the $Si\text{-}SiO_2$ structure and its impact on the normal functioning of silicon devices. We see that once again most effects occur because of the passivation layers and that only in the particular case of large doses and energetic particles do the upper layers of silicon play a part in instability phenomena.

How to use this book

This 1000- page study, divided into 18 chapters, is published in two volumes. Although the chapters follow each other in a logical order, they can be read independantly. Each one contains an abstract in English, French and German, a table of contents, a list of symbols, units and abbreviations used and a list of references. An Author Index and a Subject Index are found at the end of each volume and easily refer the reader to the relevant chapter, section or paragraph.

An ambitious European undertaking

This multi-author study is the result of four years of a fruitful European co-operation between engineers working in the silicon industry, research scientists in the field of micro-electronics and university professors. The difficulties encountered in bringing this project to a successful ending have been numerous, the major one being that English is not the mother tongue of any of the contributors. We thus ask the reader to show leniency for style and grammatical errors which have espaced our editing. A great deal of effort has also been devoted to unifying symbols, units and abbreviations as well as styles and approaches. This should make reading easier.

Acknowledgements

It is impossible, in a project of this magnitude, to thank all those who, in one way or another, contributed to its sucessful outcome.

We are grateful to those persons who, at different levels of the management of the Corbeil Essonnes plant, trusted us in spite of formidable odds.

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Finally we would like to emphasize once more that this project would not have been possible without the encouragement, the logistical support and the financial help of the IC manufacturing plant of Corbeil Essonnes, of the IBM France Cie.

Conferences of related interest

1 The international conferences on the «Physics of SiO_2 and its Interfaces» such as those held in Yorktown Heights NY (USA) 1978, Raleigh NC (USA) 1980, etc.
2 The international conferences on «Insulating Films On Semiconductors (INFOS conferences)» such as those held in Durham (England) in 1979, in Erlangen (W. Germany) in 1981, in Eindhoven (Holland) in 1983, in Toulouse (France) in 1985.

Review papers on instabilities

3 Atalla *et al*, *Bell Syst. Tech. J.* 38 (1959) 749.
4 Nicollian, E.H., Surface passivation of semiconductors, *J. Vac. Sci. & Technol.* 8 (5) (1971) 539-549.
5 Gregor, L.V., Passivation of semiconductor surfaces, *Solid State Technol.* 14 (4) (1971) 37-43.
6 Deal, B.E., The current understanding of charges in the thermally oxidized silicon structure, *J. Electrochem. Soc.* 121 (6) (1974) 198-205.
7 Schnable, G.L., Kern, W. and Comizzoli, R.B., Passivation coatings on silicon devices, *J. Electrochem. Soc.* 122 (8) (1975) 1092-1103.
8 Pliskin, W.A., Gdula, R.A., *IBM International Technical Report*, TR no. 2226 (1978).
9 Barbottin, G., Les instabilités dans les dispositifs à semiconducteurs, causes et remèdes, *Internal Technical Report, IBM Corbeil, France,* 1979.
10 Hwa-Nien Yu, Reisman, A., Osburn, C.M. and Critchlow, D.L., 1 nm MOSFET VLSI technology. I. An overview, *IEEE J. Solid-State Circuits SC-* 14, (2) (1979) 240-246.
11 Deal, B.E., Standardized terminology for oxide charges associated with termally oxidized silicon, *IEEE Trans. Electron Devices ED-* 27 (3) (1980) 606-8.
12 Lycoudes, N.E. and Childers, C.C., Semiconductor instability failure mechanisms review, *IEEE Trans. Reliab. R*-29 (3) (1980) 237-249.
13 Lile, D.L., Interfacial constraints on device performance, *J. Vac. Sci. & Technol. B* 2 (3) (1984) 496-503.

Books of related interest

14 Grove, A.S., **Physics and Technology of Semiconductor Devices** (Wiley, New York, 1967).
15 Sze, S.M., **Physics of Semiconductor Devices** (Wiley, New York, 1981).
16 **Nondestructive Evaluation of Semiconductor Materials and Devices** , edited by Zemel, J.N., Frascati, Italy, 19-29 Seot. 1978, Plenum, New York, 1979).
17 Nicollian, E.H. and Brews, J.R. **MOS Physics and Technology** (Wiley, New York, 1982).
18 Davis, J.R., **Instabilities in MOS Devices** (Gordon and Breach, New York, 1981).

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