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UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org

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**QUALIFICATION AND SURVEILLANCE LABORATORY
FOR CONSUMER ELECTRONIC PRODUCTS**

DP/CPR/85/087

PEOPLE'S REPUBLIC OF CHINA

Technical report: Electronic optical/X-ray energy spectrum analysis devices*

Prepared for the Government of the People's Republic of China
by the United Nations Industrial Development Organization,
acting as executing agency for the United Nations Development Programme

Based on the work of Wolfgang Hoppe,
UNIDO Consultant

Backstopping officer: H. Seidel, Engineering Industries Branch

United Nations Industrial Development Organization
Vienna

* This document has not been edited.

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ABSTRACT

Within in the framework of the UNIDO DP/CPR/85/087 a post 11-09 "Electronic Optical/ X-ray Energy Spectrum Analysis Devices" was carried out as a one month project. The task included mainly the training of the staff-members of the failure analysis lab at the Chinese Electronic Products Reliability and Environmental Testing Research Institute (CEPREI) in Guangzhou (The People's Republic of China) realized by lectures and briefings on various topics in the field of scanning electron microscopy. The seminar was held within two weeks and dealt with the basic principles of the scanning electron microscopy and the different special modes used in advanced laboratories for failure analysis of semiconductor devices and materials. The Chinese colleagues were taught the principles of the special modes in detail as well as the applications in the field of defect engineering in semiconductor materials and device testing.

Due to the lack of experimental equipments necessary for the application of these methods we had only discussions of practical aspects in the field of device/sample preparation for scanning electron microscopy investigations and an instruction on the use of the Monte-Carlo simulation techniques.

In the near future it is inalienable for the CEPREI to apply much more attention to the practical training of the colleagues as well as to the improvement of the electron-microscopical equipments used for failure analysis. This would be the only basis in order to put a step forward into the field of failure analysis with electron beams.

key words:

electron microscopy; electron microscopy examinations of materials and semiconductor devices; scanning electron microscopy; failure analysis; semiconductor device testing; electron-beam-induced current; electron-beam testing; electron channelling pattern; voltage contrast

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I. INTRODUCTION

The stay at the Chinese Electronic Products Reliability and Environmental Testing Research Institute (CEPREI) in Guangzhou took place within the framework of the United Nations Development Program DP/CPR/85/087. The objectives of the project are directed to improve the reliability level of consumer electronic products through exercising qualification, evaluation, surveillance and inspection on the quality of products /5/. This includes the training of the staff-workers at the CEPREI in the sense of a higher theoretical, technical and operational level of knowledge and facilities.
In connection with the development program 7 colleagues previously gave lectures on different aspects of

- organization and operation of test laboratories,
- certification of electronic components,
- qualitiy surveillance and inspection,
- failure analysis techniques of transistors /1/,
- calibration and metrology of electron equipments /2/,
- failure analysis of LSI/VLSI IC's /3/, and
- testing of LSI IC's /6/.

Caused by the further shrinkage of the device dimensions as well as the increase in the complexity of the design and the circuit speed there is a common feature in the semiconductor technology. This feature is characterized by an increasing change from the 'classical' failure analysis techniques based on electrical parameter measurements towards failure analysis techniques based on the application of electron as well as laser beams. Some consultants /1,3,6/ already touched this matter in short remarks. Nevertheless, if the CEPREI is really interested in the application of the electron-beam methods in the failure analysis of electron devices of (very) large-scale integrated circuits (IC) there is a need for an extensive training of the staff. This training has to include the knowledge about the physical background of electron-beam techniques especially the electron-sample interactions, the special equipments which are necessary for failure analysis, the different modes of electron-beam testing, and examples for practical applications.
With the letter from July 10, 1989, the CEPREI offered me their suggestions (Appendix B) after they thought the seminar had to be organized. This way I prepared the material to be talked on.

During the period from October 11 to November 7, 1989, I worked in the People's Republic of China to conduct the seminar at the CEPREI.
I arrived in Guangzhou on October 12. The following day I spent with the management of the institute. I was introduced to the subject the CEPREI is dealing with by Mr. Qui Zudong (National Project Director) and Mr. Ma Huaizu (Deputy Director of the CEPREI) . They showed me different labs and equipments used for environmental and reliability testing in order to aquaint me with the main topics.
Following this I discussed the guide line of the seminar with members of the failure analysis lab and introduced my own ideas respectively conceptions made in the previous weeks. It was obvious that the knowledge of the Chinese colleagues about the subject to be talked on based on the study of literature only. Besides of qualitative Electron-Beam-Induced Current (EBIC)

investigations on devices they had no detailed experience on the topics given in the suggestions.
From study tours carried out under the fellowship of the UNDP Mr. Gu (Mr. Yu, the other member of the study group, already left the CEPREI) and Mr. Fei had some practical experiences about the methods discussed later although the stay was long ago (UK, 1985) and covered with a widespread spectrum of topics (FRG, 1989).
Summa summarum, there was no need to revising the basic objectives of the seminar mentioned above.

After the seminar time for practical exercises at the scanning electron micoscope (SEM) Philips 505 of the failure analysis lab was planned. Unfortunately the SEM was out of order and till to the moment I left Guangzhou there was no possibility to repair it. Practical exercises in this direction were limited to discussions on topics in the field of sample preparation and to computer works based on the application of the Monte-Carlo simulation progam ("MC-SIM" published by NAPCHAN) concerning the calculation of the electron-hole pair generation volume.
One afternoon we spent the seminar at the Department of Physics of the South China University of Science and Technology. In this lab they are working with a transmission electron microscope (TEM) and are able to deal with the electron channelling pattern (ECP) mode by using a scanning attachement. We took the opportunity for practical exercises.

II. AGENDA

The main topics requested for the seminar by CEPREI were arranged as a lecture course estimated for a duration of two weeks.

The agenda of this course covered five main topics:

1) basic principles of the Scanning Electron Microscopy (SEM),

2) Electron Channelling Pattern (ECP),

3) Electron-Beam Induced Current (EBIC),

4) Electron-Beam Testing (EBT) and

5) future trends in the failure analysis with electron and laser beams.

In the following the five lecture titles are briefly described.

Basic principles of the SEM (2 days):

- *electron-beam micro-characterization*
  survey of different diagnostic methods and the subject of information they are dealing with
- *basic principles of the scanning electron microscopy*
- *equipments the scanning electron microscope is built of*
- *electron-specimen interaction; electron-beam damaging*
  especially in the sense of the investigation of semi-conducting materials (surface charging;defect generation)
- *low-voltage SEM*
  briefing about recent developments in the application of low-voltage sources caused by the demands of the semi-conductor technology

Electron Channelling Pattern (3 days):

1. The Origin of the Electron Channelling Pattern
1.1. Theory
wave and particle picture of the interaction between primary electrons and the lattice atoms

1.2. Experimental Verification
Conditions for measuring ECP
Equipments (WAECP, SAECP)
Signal processing
Sample preparation

in detail about necessary modifications at the SEM ; different types of electron-optical columns to achieve wide and small area ECP;

2. Properties of the ECP
to discuss the different properties of the ECP and their relations to the crystal structure of the sample under investigation

3. Application of the ECP
3.1. Width of the channelling bands: lattice parameters
3.2. Defect determination
3.3. Determination of crystal structure
3.4. Determination of crystal orientation
includes an example for a complete orientation determination (cubic system)

4. Future trends
to explain that the ECP as a modern diagnostic tool is undergoing a recent development;
the ECP could combine high resolution imaging of topographic details, mapping of the distribution of semiconductor parameters (diffusion-length; life time) with the determination of the crystal structure in very small areas (below 1 μm)

Electron-Beam-Induced Current (4 days):

1. The origin of the Electron-Beam-Induced Current
1.1. Electron-hole pair generation
1.2. Diffusion and recombination
1.3. Charge collection
1.4. The origin of the EBIC contrast
1.4.1 Diffusion-length inhomogeneities
1.4.2 Dopant inhomogeneities
1.4.3 Defect contrast

2. The EBIC technique
2.1. Principles of the EBIC mode in the SEM
2.2. Experimental set-up
2.3. Preparation

3. Quantitative measurements
3.1. Diffusion-length determination
3.2. p-n junction delineation
3.3. Temperature measurements of p-n junctions

4. Application in the field of microelectronics
4.1. Defect Engineering
connection of diffusion-length parameters with the material structure
(for example content of interstitial iron in boron-doped silicon)
4.2. Silicon-on-insulator technique
defect engineering at laser-beam recrystallized samples
4.3. Short-channel MOS transistors
theoretical treatment of EBIC data to calculate geometrical parameters of small devices

5. Current state and future trends in EBIC measurements

Voltage Contrast (3 days):

1. Basic principles
1.1. Secondary electron emission
1.2. Qualitative / Quantitative voltage contrast

2. Equipments and measuring conditions
2.1. Building equipment
2.2. Electron probe
2.3. Spectrometer
survey of different types of spectrometers and the parameters (time,voltage, and lateral resolution) achieved with them
2.4. Voltage, time, and spatial resolution
2.5. Detection systems for quantitative voltage contrast
2.6. Signal processing

3. Electron-Beam Testing techniques
3.1. Quantitative techniques
static voltage contrast; waveform measurements;
3.2. Qualitative techniques
voltage coding; stroboscopic modes; logic state mapping; frequency tracing/mapping

4. Electron-Beam Tester
(a survey of commercially available Electron-Beam Tester)

5. Electron-Beam Test methodology
5.1. Chip verification
5.2. Failure analysis

6. Future Trends

<u>**New electron-optical instruments for failure analysis (1 day)**</u>

- *mainly focussed on the development trends in the case of high speed circuits*
  - ... *photoemission waveform measurements*
  - ... *picosecond photon-SEM*
  - ... *testing equipments basing on the electro-optic effect*
- *briefing of the main applications of laser scanning microscopy*
- *briefing of different aspects of the scanning tunneling microscopy as a new tool among the diagnostic methods*

A comprehensive collection of lecture material was brought to China and used in demonstrations. A number of recent publications on the subject we talked about was given as a gift. The Chinese colleagues copied the hole manuscript (120 pages) of the seminar and the Monte-Carlo simulation program published by NAPCHAN in 1989.
The class of students consisted of 13 CEPREI staff members and 7 guests from other institutes recorded at the on-coming seminar. The number of participants changed in correlation to the specific topics under discussion. The seminar consisted of morning and afternoon lectures. A splitting in morning lectures and afternoon question and discussion sessions was refused by the Chinese colleagues.

III. OBSERVATIONS

As I mentioned above I got the impression that the Chinese colleagues at the CEPREI are standing at the beginning to use electron-beam techniques as failure analysis modes. Up to now they are using the SEM in three ways mainly:

1) observation of the surface topology of semiconductor devices with the help of the conventional secondary electron contrast;
2) micro-analytical investigations with wave-length and energy-dispersive x-ray spectrometers attached at the SEM and
3) qualitative analysis of EBIC distributions observed at semiconductor devices.

There is a complete lack of experimental equipments necessary for all modes of voltage contrast techniques except the qualitative voltage contrast mode which is observable in every conventional SEM but used as an "entry" mode to analyse hard errors only. But neither a beam blanking unit necessary for the investigation of time-dependent processes nor simple signal-processing equipments necessary for quantitative evaluation are available. In addition, it was very difficult to get any detailed information about the present-day state of the technological level which characterizes the Chinese microelectronic manufacturing as well as about the failure analysis problems the CEPREI is faced with. This includes the information about both the width of the conduction lines and the working frequency of the circuits. The knowledge about these parameters is important to decide what are the next steps ingenious for the step-by-step introduction of the electron-beam testing.
The failure analysis lab has a sophisticated system of different equipments used for the encapsulation of ready devices (mechanical; wet and dry etching) in agreement with the current tasks of failure investigations. In order to enhance basic research work in electron-beam failure analysis the equipments have to be completed by evaporation, lapping/polishing, and wire bonding machines. The equipments mentioned first could be used to produce Schottky barriers (EBIC) and the other for mechanical probe treatment in order to achieve depth-related information. Manual wire-bonding machines are useful to make electrical contacts on different types of small numbers of test chips (EBIC; voltage contrast).
The continuous service of the sophisticated microscopic equipments given by the enterprises from abroad seems to be a serious problem for the Chinese colleagues (CEPREI; South China University). But this is important to meet the requirements of both a continuous running and a complete use of all SEM functions.
The problems concerning the frequent breaks in the power supply are mentioned already by former consultants. It should be emphasized once more. The vacuum system should not be turned off to secure the best vacuum conditions.

IV. RECOMMENDATIONS

As a result of my stay at the CEPREI summarized from my impressions achieved during the seminar as well as during the visit in the test and failure laboratories of the CEPREI I made several recommendations.
These recommendations are dealing with both improvements in the abilities of the colleagues working at the SEM and improvements of the installed equipments which are necessary for failure analysis in the range of V(U)LSI technology.

A) Investment of equipments :

- 'zero' level (to make by CEPREI own workshop)

  different kinds of sample holders for EBIC investigations (mechanical prober stage; designed for bevelled and cleaved samples; including temperature-dependent measurements)

- small level (**below 50 000 $**)

manual wire bonding machine	(≈ 40 000 $)
precision lapping and optical polishing machine	(≈ 2 000 $)
current amplifier (picoammeter with selectable input resistance [EBIC,EBIV], range ...)	(≈ 5 000 $)
sputter coater	(≈ 5 000 $)
turbo coater	(≈ 15 000 $)
beam blanking unit	

- expensive level (**in the range of 300 000 $**)

  advanced framestore and image acquisition system for SEM's (to be able to work in a more quantitative manner)

- advanced level (**more than 300 000 $**)

  Electron-Beam testing equipments (≈ 350 000 $)
  (consist of spectrometer, beam blanking, DUT, and computer system which adopt a conventional SEM for function testing and failure analysis)

  Electron-Beam Tester (≈ 700 000 $)
  (low-voltage SEM used only for function testing and failure analysis)

B) Staff training program

- It seems to be useful to continue the theoretical orientated seminar in failure analysis with a second practical orientated part. This course should be provided the training carried out at modern SEM equipments, should be dealed with current problems of EBT, and should be given for 2 Chinese colleagues for a duration of 3 month.
  This service could be arranged at our diagnostic department (Institute of Semiconductor Physics, Frankfurt (Oder)).

- stronger cooperative exchange with the semiconductor industry

  ... to get a better understanding of the basic technologies applied in the semiconductor manufactoring and

  ... to realize an exchange of knowledge and equipments used in the field of failure analysis;

The training concepts of the operational staff should be reviewed:

- stronger correlation between going "abroad" for practical training on one side and the current equipment standard available at the CEPREI on the other side;
  Aim: to realize a fast transfer of valuable information gained during the stay abroad (without any time delay)

- in order to prepare the right decision for the investment policy of the CEPREI on the field of EBT;

These recommendations were made to the CEPREI management represented by Mr. Ma Huaizu at the end of my stay in Guangzhou.

V. Acknowledgments

I wish to thank Mr. Ye Yuqing, CEPREI Director, the engineers of the failure analysis laboratory, the other attendees of the seminar, and the members of the Office of Foreign Affairs (CEPREI) for their co-operation; Mr. Gu Guanhua for translating the lectures for the attendees; Mrs. Zhang Xi Wei (Program Officer UNDP Beijing); and Mrs. Tian Hui Wen (member of the CEPREI Beijing).

APPENDIX

A List of the students/ attendees to the seminar

Name	Occupation	Organization
Shi MingZhe 施明哲	engineer	the Failure Analysis Centre of CEPREI
Xiao JinSheng 肖金生	engineer	the Failure Analysis Centre of CEPREI
Xu Ai Bin 徐爱斌	engineer	the Failure Analysis Centre of CEPREI
He XiaoQi 何小琦	engineer	the Failure Analysis Centre of CEPREI
Chai HuiZhen 蔡惠珍	engineer	the Failure Analysis Centre of CEPREI
Kong XieDong 孔学东	engineer	the Failure Analysis Centre of CEPREI
Fei QingYu 费庆宇	engineer	the Failure Analysis Centre of CEPREI
Gan PuShen 甘普生	engineer	the Failure Analysis Centre of CEPREI
Yu HangLin 禹航林	engineer	the Failure Analysis Centre of CEPREI
Lin Yu 林煜	engineer	the Failure Analysis Centre of CEPREI
Chai Yi 蔡懿	engineer	the Failure Analysis Centre of CEPREI
Ning DongHong 宁冬红	engineer	the Testing Centre of CEPREI
Huang YueChun 黄岳春	engineer	the Testing Centre of CEPREI

Name	Occupation	Organization
He HuiZhen 何惠珍	lecturer	the Material Structure Analysis Centre of the GuanDong Institute of Technology
Yan KeShan 源可珊	engineer	the Material Structure Analysis Centre of the GuanDong Institute of Technology
Li QingXiang 黎庆翔	engineer	the GuanDong Bureau of Import & Export Commodity Inspection
Shi TuKeng 司徒铿	assistant engineer	the GuanDong Bureau of Import & Export Commodity Inspection
Lu You 吕铀	engineer	the Geology & Mining Industry Bureau of GuanDong
Hu JingShu 胡瑾肃	assistant engineer	the Geology & Mining Industry Bureau of GuanDong
Chen ZhongMin 陈钟敏	assistant engineer	the Non-iron Institute of GuanDong

B Contents of the seminar proposed by the CEPREI

1/

Suggestions on the Contents for the Seminar

A. The Principles and Applications of SEM

1/ The Basic principle of SEM and its operations;

2/ Briefing on various SEM optional parts used to develop SEM functions of analysing, testing and processing the image or data; Discussions on their applications in the failure analysis of semiconductor devices;

3/ Briefing on the observation and analysis of the surface shape of semiconductor devices or materials by means of Secondary Electron Imaging (SE);

4/ The principle of various operational modes of Voltage Contrast (VC) and their applications in the failure analysis of semiconductor devices;
Including: static, dynamic, quasi-static, clock-stretching, synchronous, stroboscopic and full quantitative VC imaging;

5/ Discussions on the dynamic range, voltage resolution, voltage contrast sensitivity and voltage accuracy of the quantitative measurements. How to remove the effect of pure secondary electron imaging in voltage contrast imaging?

6/ The charge induced by SEM electron beam on the surface insulation layer of semiconductor devices:
Discussions on :
-- The unfavourable effect to voltage contrast imaging;
-- The way to overcome this trouble;

7/ The relationship between the primary beam energy and the distribution of electron-beam induced defects density on semiconductor materials;

8/ The principle and application of electron beam induced current (EBIC) in failure analysis of semiconductor devices;

9/ The methods of and your personal experience in utilising the EBIC mode to measure semiconductor physical parameters and device parameters, such as:
-- junction width and depth below the surface;
-- the diffusion length and surface recombination rate of minority carriers;

2/

--the life of minority carriers;

-- the temperature of P-N junction;

10/ The application of backscattered electron imaging (BS) in the analysis of semiconductor materials and devices;

11/ Determination of crystal structure and orientation from electron channelling patterns;

* 12/ Briefing on the principle and equipment of SEM stroboscopic voltage contrast imaging and its application in failure analysis of semiconductor devices/integrated circuits;

* 13/ Briefing on the principle and equipment of SEM non-contact electron-beam testing and its application in the analysis of VLSI;

B. Briefing on the various new electronic optical instruments and their applications. Review of the development trend of new electronic optical instruments

C. Question and Answer Sessions and on-spot demonstrations in the Lab

* 12/ and 13/ are special requests.

C List of used reports from former consultants

/1/ DUMAS JM.: " Failure Analysis of Transistors "
December 1983

/2/ QUINN CL.: " Calibration and Metrology of Electronic Equipments "
March 1984

/3/ TRAPP OD.: " Failure Analysis of IC's "
July 1984

/4/ GU G. and Yu S.: " Report from Fellowship Training in Failure Analysis of Microcircuits and Scanning Electron Microscopy"
October 1985

/5/ Terminal Report of the CEPREI National Counterpart; July 1988

/6/ BROWN J. : " Testing of large-scale IC's "
March 1989