PROC. 15TH INT. CONF. PHYSICS OF SEMICONDUCTORS. KYOTO, 1980
J. PHYS. SOC. JAPAN **49** (1980) SUPPL. A p. 1309—1317

CLOSING ADDRESS

Yasutada Uemura

Department of Physics
University of Tokyo
Bunkyo-ku, Tokyo
Japan

Mister Chairman, fellow participants,

It is a great honor for me to stand here to give the closing address, but at the same time this is a very difficult task for me because we have already heard so many distinguished closing addresses in the past conferences that there seems to be no room left for any innovation, even though semiconductor physicists have been star champions of innovations. In his opening address, the conference chairman told us the scope of the conference succinctly and clearly in the form of a historical view. Therefore, I will follow his example and extend it to summarize the results of this conference and to present my conclusion on the recent trends of semiconductor physics.

Before talking about physics, I will show some statistics of this Kyoto Conference and compare with those of the previous Kyoto Conference of 1966. As shown in Table (1), this time we had 806 delegates, 327 coming from abroad and 479 from within Japan. In total 244 papers were presented, 212 contributed, 28 invited and 4 in plenary sessions. A total of 628 papers were submitted for presentation.

The international program committee made a great effort to organize the program. A full meeting of this committee was held in Tokyo including seven members from abroad. The members of the organizing committee have asked me to express their gratitude to those of you who submitted papers for presentation. They were sorry

Table 1

	1980 (KICH)	1966 (K.K.)
DELEGATE	806	550
FROM ABROAD	327	223
FROM JAPAN	479	327
PAPERS (PRESENTED)	244	147
CONTRIBUTED	212	122
INVITED	28	17
PLENARY	4	8 (REVIEW)

Table 2

READING	1950	
AMSTERDAM		THE DAWN OF
GARMISCH		MODERN
ROCHESTER		SEMICONDUCTOR
PRAGUE	1960	PHYSICS
EXETER		
PARIS		EXTENSION
KYOTO		AND
MOSCOW		SOPHISTICATION
CAMBRIDGE	1970	
WARSAW		
STUTTGART		SIGN OF
ROME		TRANSFORMATIONS
EDINBURGH		
KYOTO	1980	

that many good papers were not accepted because of the severe limitation on time and the number of available sessions.

These numbers in Table (1) are not so much different from those of recent conferences; for example of Edinburgh and of Rome. However, you can find considerable changes if you make a comparison with the previous Kyoto Conference of fourteen years ago. Generally speaking, similar changes are also seen in the content of the physics to be discussed. Fourteen years have brought considerable changes in the fields of interests, in the method of investigations and in materials to be studied.

Table (2) is a chronological table of every semiconductor conference, and headings on the right characterize the three decades since 1950.

The first decade starting in 1950 can be characterized as the dawn of modern semiconductor physics opened by the discovery of transistor action. A high purity single crystal of germanium was not only the key material of the newly developed transistor technology but also the main actor on the stage of basic physical research during this decade. I do not need to refer to many famous papers here because you can easily recall them at present as the "classics" of the field. Many important works contributed at Amsterdam told us of the coming of age of germanium studies which reached the peak at Rochester.

The difference between industrial and academic researches is very small at that time, and many physicists and engineers in both sectors met and discussed together in one room at the same conference. Dislocations, recombination life times of minority carriers and avalanche breakdown of p-n junctions were examples of common interest to both academic and industrial researchers. We might say that two sectors were in their honeymoon and as a result the tunnel diode was born.

Presumably, older participants here who once played major roles in those young and animated days of semiconductor physics may recall their younger days with some kind of emotional sentiment.

As to the heading for the second decade, "extension and sophistication" was chosen from the main theme of the opening address at the Cambridge Conference in 1970. Various kinds of accurate and sophisticated knowledge had been accumulated for bulk single crystals because of the extension in the kind of materials, in experimental techniques such as modulation and laser spectroscopies and in methods of theoretical computations. Distinguished critical summaries were given in the opening address at Cambridge by Prof. Lax and in the concluding talk at Stuttgart by Prof. Cardona for the progress made in the decade which had just past. Therefore I will not describe it here except to say that semiconductor physics was at one of the peaks in the mountain range of solid state science.

The semiconductor technology, too, became a star of modern industries with newly developed devices such as Si-MOSFET, junction lasers and Gunn diodes, so that the term "solid state electronics" became a household word and began appearing even in TV commercials. However, we should not omit the start of a very important and new technological development, namely that of integrated circuit. It was an embryo of the L.S.I. and V.L.S.I. recently developed to meet the ever escalating need for larger and faster computers.

Sophistication in academic research and the start of a new development in industrial research brought about the end of the honeymoon enjoyed by the two sectors. From then on, solid state physicists and device physicists and engineers began to walk their own separate ways and to organize their own conferences separately. At the same time, a rapid growth in the number of specialists made it impossible to meet together in a single large scale conference.

That is one of the characteristics of semiconductor physics at the end of the second decade.

We are now in the year 1980, the end of the third decade, and we must find a suitable heading which characterizes this past decade.

Of course, one can recognize steady and continual developments in various fields of semiconductor physics. However, the birth and rapid growth of new fields during this decade have been so remarkable that trends in research seem to indicate a sign of transformations. Therefore, I would like to propose the heading "sign of transformations" tentatively, as shown in Table (2). You may ask what is meant by the word "transformations." Let me sketch the recent trends of semiconductor physics a little bit more in detail to make the meaning of this word clear. Main subjects of the sketch are shown in Table (3).

It is quite certain that the transformations have partly been brought about by technological impacts. The difference between academic and industrial research has again become small because of shared interests, although large numbers of researchers in both sectors have made it impossible to organize a single large conference. To remedy this situation and to build bridges between these sectors, a special session has been organized in our conferences since the Rome Conference of 1976.

This time, reflecting the recent interests in material technology for L.S.I. and for optoelectric devices, two challenging talks to semiconductor physicists were presented to stimulate various comments and discussions [S-1][S-2]. This is a new form of running a session. Thanks to the chairmen, speakers and commentators, we had a fruitful time for both sectors through the valuable comments and discussions.

After the introduction of the laser in the second decade, continuous growth has been shown in the optical studies. Light scattering has proved to be a powerful tool in the third decade for the investigation of carriers, phonons and their interactions. In this

Table 3

Special Session
Optical Studies (Exciton)
Hot Electrons
Amorphous Semiconductor
Surface and Interface
Deep Level Impurity
Electronic Theory
Impurity Conduction
Many Body Effect
Space Charge Layer, Superlattice
Electron-Hole System
Various Phases
New Materials

conference, a dispersion relation of the exciton-polariton mode observed by the resonant Raman scattering method was reported [VIII-1]. I learned, in one of the plenary sessions on Monday, that both the sign and magnitude of the electron-phonon coupling constant can be determined by this method [P-2].

This afternoon, a new optical bistability which is interesting to both physics and device applications was reported for GaAs and InSb [IX-7].

I might say that a transformation in the object of optical research from static to dynamical phenomena is gradually taking place, although many important papers have been contributed on precise spectroscopic analysis of exciton levels in recent conferences. The recent development in picosecond pulsed laser technique has also emphasized the investigation of dynamical processes in optical phenomena.

The "hot electron" field is a pioneer in revealing a transformation from static to dynamic which has taken place since the middle of the second decade. A current interest seems to be to find a very specific distribution of carriers in phase space caused by high fields such as those caused by the so called typical streaming effect as reported at Edinburgh and at Kyoto this time [IV-12] [IV-13]. The distribution is quite different from those described by the original electron temperature concepts.

A typical example of fields in rapid growth is the study of disordered or amorphous semiconductors. Since Cambridge, we have had a talk on this subject in a plenary session in every conference. The growth in the number of contributed papers on this subject was such that seven sessions had to be organized including laser annealing in Kyoto this time.

Considerable progress has been made in the study of microscopic mechanism by hydrogenated amorphous Si, and a session on flourinated amorphous Si was added as a newcomer in this conference. I suppose that a cooperation of these complementary elements help to clarify the nature of bonding in these materials.

Amorphous states are metastable so that atomic rearrangements play an important role in thermal and optical processes. Another newcomer session was that on laser annealing. The intense laser irradiation causes a very rapid recrystalization of the amorphous region obtained by ion inplantation. What is the main mechanism in this process? Two invited talks have suggested two different kinds of interpretations [XXIII-1][XXIII-2]. Through the discussions in this session, the physics involved in this complicated process was elucidated. Many interesting problems suggested there will lead to further investigations.

Another interesting material is chalcogenide glasses. As shown in the plenary session of Thursday, the model of charged intrinsic defects state with a negative effective correlation energy has been proved to be very successful by introducing some additional defects to explain various experimental data of photoluminescence and of photo chemical processes [P-4].

Surface and interface studies have made remarkable progress in this past decade as a result of new experimental methods such as photoemission, XPS, ESCA, synchrotron radiation and so on. Various spectroscopic data on the surface electronic states have been accumulated since the Stuttgart conference. This time, the pinning of Fermi level caused by the presence of interface states was reported in which an unified model was proposed to describe the pinning for various kinds of interface [XX-11].

In the field of deep impurity states similar types of progress have been recognized in the past decade as those in the surface and interface. The rearrangement of host atoms at the interface or near the impurity atom are very important again as well as the dynamical displacement of these atoms. In this conference, the intrinsic and the defects induced surface reconstruction of silicon [XX-1] and the atomic displacement caused by the radiationless recombination via deep levels in III-V compounds [III-1][III-2][S-2] have been discussed intensively.

As already mentioned, all these rapidly growing fields have been partly stimulated by innovations in recent technologies such as solar cells, I.C. and L.S.I. and optoelectric devices. However, I will remind you that they are all closely related to a sign of transformations in very basic theoretical studies. Indeed, this is a traditional characteristic of semiconductor research.

In the theoretical investigations of electronic structures in deep level impurities, in disordered or random systems and even in surfaces of atomic scale, one has to depart from three dimensional k space representation and transform it into R space representation which has been shown to be a powerful method for making connection with intuitive chemical bond pictures and for explaining various spectroscopic data. The terms "bands and bonds" representing two different concepts have been used frequently in the first half of the decade and a firm theoretical basis to bridge these concepts was presented in the first plenary session on Monday and in two invited talks on Tuesday afternoon [P-1][III-5][III-6].

The relaxation of surrounding atoms and the correlation among trapped carriers are also very important in the theoretical studies of deep trapping states, and a theoretical confirmation of the presence of the so called effective negative correlation energy was presented for a multiply charged vacancy in Si as a cooperative effect of exchange, correlation and lattice relaxation [III-5] [III-6].

Transport phenomena in random systems have interested many of us since impurity band was first discovered in 1950. According to the regime of carrier concentrations, important theoretical concepts and models have been brought into the field; namely metal-insulator transition, minimum metallic conductivity, negative magneto-resistance caused by localized spins, variable range and correlated hopping etc. A continual development of experimental investigations was reviewed in a plenary session with some recent results at very low temperature [P-3].

I will remind you, that a new type of negative magnetoresistance of orbital origin was first observed in the metallic regime of two dimensional carriers in the MOS inversion layers as reported this afternoon [XVIII-12]. I suppose that two dimensional carriers will initiate an important transformation in the future studies of this field theoretically and experimentally.

Now I would like to call your attention to many body effects. Recent developments in band theory were reported in the first plenary session and in an invited talk on Monday. Both talks were based on the density functional treatment of the many body effect for the ground state [P-1][I-1].

Thanks to the technology of MOSFET and artificial super lattice, the studies of quasi two dimensional subbands have shown a rapid growth in this decade both theoretically and experimentally. The invited talks, in the sessions for space charge layer and superlattice, reviewed the developments in which quantization and many electron effects in subband structures were clearly and quantitatively demonstrated because of the controlability of carrier concentration over a wide range [XVIII-1][XVIII-2][XIX-1]. Self-consistently determined charge distributions play an essential role for obtaining these results. This is also true in determining the band structure of intercalation compounds as shown during this conference [XVII-6][XVII-9].

A strong interaction between carriers, or between carriers and phonons causes a phase change.

A typical example is the electron-hole system. The presence of excitons, or of exciton complexes, or of electron hole liquid or plasma depends on the concentration of electron-holes and on temperature. Controlled laser irradiation and indirect recombination processes produce favorable conditions to realize various phases experimentally. The field has shown a rapid growth since the Warsaw conference with very interesting visual experimental results. This time, an experiment on droplets interacting with phonon winds was demonstrated [VII-4].

Current interests in new phases of charge density wave, of Wigner lattice and of superconductivity promote research for various new materials. Indeed, increased activities in experimental research on these new materials have been a characteristic feature of the past decade. Layered compounds of transition metal dichalcogenide, of graphite intercalation compounds, $(SN)_x$ and chained organic crystal such as TTF-TCNQ are typical examples of new materials. The research has been motivated not only by industrial needs to find materials for high T_c superconductors or for batteries, but also by rather academic interests of many body interactions.

In this conference, the discovery of a superconducting state in a quasi one dimensional conductor $(TMTSF)_2PF_6$ was reported [XVI-1]. This material is expected to show an interesting phase diagram suggesting the competing mechanisms of the so called Pierls transition and superconducting transitions. Structural instability is also expected in these materials as well as IV-VI compounds as presented in the session on phase change [XIII-1]. Experiments using high pressure have been shown to be very useful in these studies.

As for magnetic interactions, a new category has been created. It is so called "Semimagnetic semiconductor" such as $Hg_{1-x}Mn_xTe$, having narrow band gap and spin glass systems. We have invited talks in Edinburgh and in Kyoto this time again [XV-1]. After basic experimental investigations, the microscopic mechanism of spin-spin interaction will be clarified in the near future.

Table 4

Sign of Transformations

Bulk ⟶ Surface and Interface
Shallow ⟶ Deep
Periodic ⟶ Random or Disordered

$\vec{k}$ Space ⟶ $\vec{R}$ Space
Weak Coupling ⟶ Strong Coupling
Static ⟶ Dynamic

Three Dimensional ⟶ Low Dimensional
Natural ⟶ Designed

To summarize what I have been talking about, I will show in Table (4) the major signs of transformations as I see them. "Transformations" in Table (4) should proceed from left to right. The first three are those with respect to fields of study, the second three are with respect to phenomena or to theoretical bases and the last two are with respect to materials.

In the opening address, it was predicted that this conference would be recalled as a turning point of semiconductor physics. I think that my conclusion is consistent with that prediction. However, I am still afraid that my sketch and summary of this conference may be too personal. No doubt, I have committed sins of ommission and commission for which I ask your indulgence.

By now, you are all familiar with the symbol shown in Fig. (1). It was designed by Prof. Eiichi Hanamura. Someone raised the

Fig. 1

question "what does this symbol mean?" in the organizing committee meeting. Another person remarked "It is so abstract that anyone can superpose his own image of semiconductor physics, therefore it is a good design." I think the same can be said about my heading for the achievement of the past decade. I hope that all of you will draw your own conclusion on the meaning of the abstract heading of "transformations."

What about the next decade? I do not know. Instead of playing the role of a fortune teller, I will call your attention to a "new material" discovered nearly 150 years ago.

During the course of his studies on electricity in various materials, the famous Michael Faraday was surprised when he discovered the strange temperature dependence of electricity of sulphuret of silver. It was indeed a new material at that time in the terminology of our conference. After describing his careful observations of the interesting characteristics of this material when it was heated on a lamp, he closed his detailed descriptions by the sentences shown in Table (5) which were published in the Philosophical Transactions in 1833. We may choose this date as the birthday of our semiconductor physics.

Table 5

There is no other body with which I am acquainted, that, like sulphuret of silver, can compare with metals in conducting power for electricity of low tension when hot, but which, unlike them, during cooling, loses in power, whilst they, on the contrary, gain. Probably, however, many others may, when sought for, be found.

You can sense from these sentences, Faraday's almost naive and simple surprise and joy over his discovery. You can also sense his optimism that many new materials will be found in the future. His optimism was not brash or contrived to get more research fund from the government or a foundation; it was based on his conviction of what nature held in store for the future generations of scientists. If we all follow his spirit of optimism, I think that the progress of semiconductor research in the following decade will be as great as that in the past, and that many of you, particularly younger scientists will experience many surprises and joys as experienced by Faraday.

On behalf of the organizing committee, I wish to take this opportunity to thank all of you for your cooperation in carrying out this conference smoothly to the end. I look forward to meeting many of you again in two years time in Montpellier.

Thank you.