Solid State Science

Past, Present and Predicted

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Preface

HISTORY AND PREHISTORY

The articles in this book sketch the history, present achievements and potential of the science of the solid state. The authors are drawn from many corners of the subject and have been chosen to provide a balanced overview, accessible in part or in whole to a wide readership.

All too often diverse styles and purposes have obscured the unity of solid state science. We see a need to affirm its identity, unity and importance in science today. The last twenty years have seen it replace nuclear physics and radiocommunication as the branch of science most affecting our daily lives. Whilst it has become a cliché to speak of the 'Age of Silicon', how many people understand how our present devices came to be invented, and in what directions they are evolving at the present time? Our aim, therefore, is to trace the roots of solid state science, follow the development of its main branches and indicate some probable future developments.

Most histories of early physical science concentrate on the more idealised models and fundamental laws, neglecting the great mass of work which has been concerned with the investigation of real materials. This is the prehistory of solid state science, about which Cyril Stanley Smith writes in Chapter 2, and has written for many years with eloquence and insight. He has also offered inspiration to those who follow: 'In the history of the pure sciences, the richest opportunities lie in the area of solid state physics. Not only is this the largest sub-field of physics today, but it is changing the concept of what physics can be. The boundary conditions no longer need be those of idealised atomism and simple symmetry, but include imperfections and real structures.'

While the study of the early predecessors of solid state science offers fascinating insights, the subject did not acquire a separate identity or a coherent basis until the 1930s. It needed the methods of quantum mechanics which were developed in the 1920s to turn the arts of using materials in metallurgy, engineering, crystallography, chemistry, magnetism, optics and electronics into sciences. In every case the same quantum mechanical rules for the formation of solids and their resulting properties offer insight, understanding and predictive power. All were revealed as branches of the single new field of solid state science; as illustrated in figure 1. In relation to

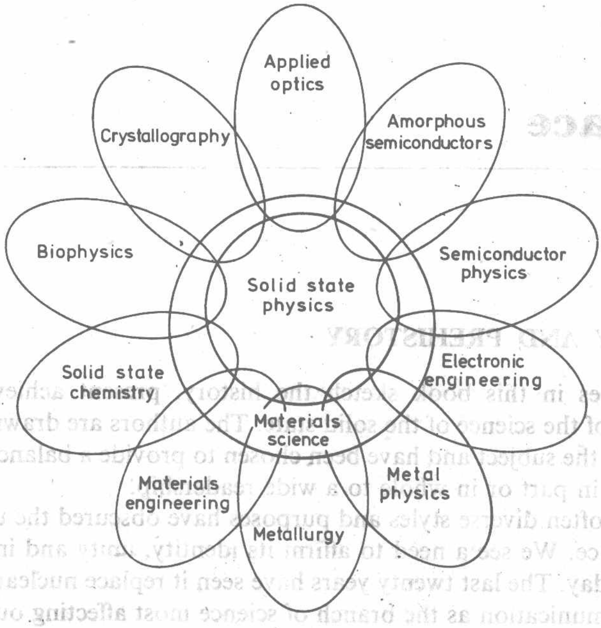

Figure 1 Some of the major overlapping research fields within Solid State Science. Solid State Physics is at the core of nearly all fields, while Materials Science embraces the wider application of the basic studies.

many of the problems which it hoped to solve, solid state physics was therefore a late starter and it was for long preoccupied with explanation rather than prediction. A good example is that of the photographic process, which is based on some very subtle physical and chemical effects in silver halide crystals. Invented in the nineteenth century, it was tentatively explained only in the late 1930s, by Mott and Gurney. N F Mott, in his recent autobiography, notes how belated his theory was from an industrial point of view, however intellectually satisfying it may be. A delightful extension of their theory came much later when direct photography from a positive became available. The migration of *electrons* in the classic process makes a *negative*, but holes migrate in the opposite direction and can be persuaded to make a *positive*. Today, the tables are turned; solid-state-related industries neglect basic research at their peril.

Even that rich period of the development is poorly understood and little appreciated, despite the fact that some of its most heroic figures, such as Mott, are still with us. The current International Project on the History of Solid State Physics will do much to remedy this and its archives will provide the raw material for a generation of science historians. In due course, a coherent picture will emerge. This book attempts only a modest contribution towards that end.

DIVERSITY AND DIVERGENCE

Why has this process, by which the identity of such an important field becomes established, proved so laborious? The reason must lie in the bewildering diversity of the solid state both as regards physical phenomena and applications. No central single quest—'split the atom', 'plasma fusion', 'find new particles'—has focused the solid state scientist's activities. His explorations have been like those of the Victorian plant collectors, searching for exotic and unusual specimens, and adding them to his collection. The subject has lacked a Charles Darwin who could classify all the information around a single grand theme. Instead we divide it up as we see fit for the purposes at hand; for the subjects of conferences, for publishing, or for the convenience of university administration. Figure 2 shows a classification by *structure*. It fails completely to recognise the diversity which nature gives us within even an identical structure, such as that of a single crystal.

Figure 3 attempts a classification by *type of material*. The four sectors certainly point as four signposts to different directions of solid state science. Again they are useful in practice—as in the journals of The Institute of Physics. However, as a classification, they are too coarse. A single crystal insulator may be studied in order to probe its structure, mechanical properties, magnetism, conductivity, or optical properties. This suggests an interleaving classification based on the *object of study*, as attempted in figure 4. It is this type of classification which is used in abstracting journals such as *Physics Abstracts*. This is a more contentious classification since it is continually evolving, often undergoing fission into separate subfields. Such a tendency is sometimes deplored, but is probably quite healthy. Returning to

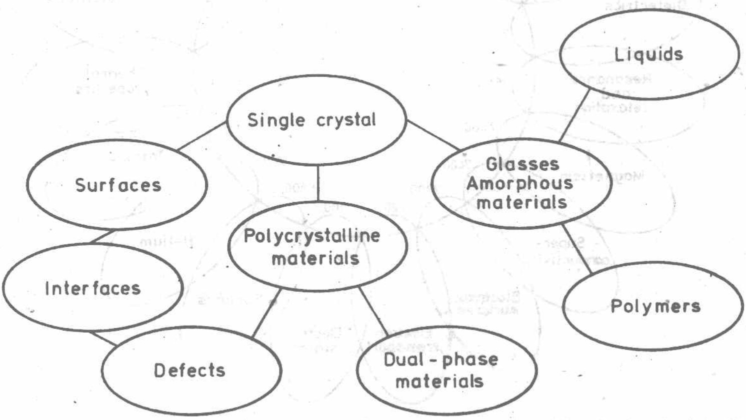

Figure 2 A classification by structure. There are relatively few distinct types of structure encountered in solid state science. A single crystal sample can be viewed using a host of different techniques and so contribute to our understanding of many branches of solid state science.

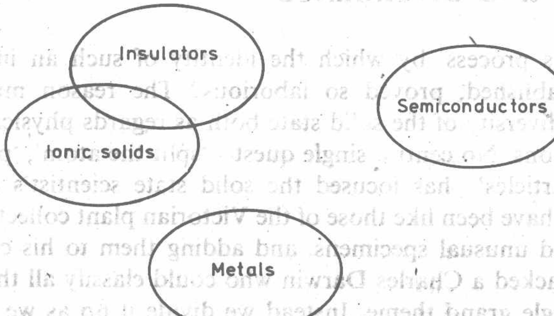

Figure 3 A classification by type of material. The basic electronic properties of materials provide a basis for a useful classification according to the nature of electron states in the material. Again any one type of material, such as a metal, can be examined using a host of techniques for a variety of objects of study.

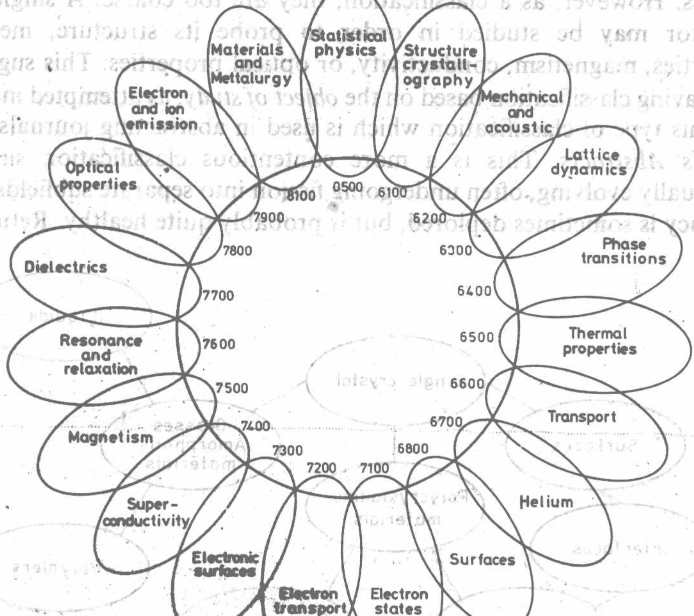

Figure 4 A classification by object of study. While it is clearly useful, this classification is open-ended and is boundaries are largely a matter of convention and opinion. The choice here is the official one devised by *Physics Abstracts* and used by many journals to help the working scientist find papers close to his chosen interests.

our botanical analogy, gardeners will find a ready parallel in the growth of perennial plants. As each clump expands its centre dies, partly of old age, but essentially by being denied the resources for growth by the vigorous outer ring of young growth. The prudent gardener divides the young growth into separate pieces, each of which has room to grow. This process of definition and division is often defeated by further growth, causing individual subfields to coalesce. Many key words of our subject (magneto-optics, thermo-electricity) carry this message. The same process brings a subfield into closer contact with neighbouring fields and hybrid subjects are formed. This presents problems of classification. Does the transport of ions in solids belong to physics or chemistry? Do semiconductor devices belong to engineering or physics?

Perhaps the least satisfactory classification (but one which classifies the scientists themselves rather well) is that determined by *technique*. This topic is pursued in Chapter 12. Some techniques, like the de Haas–van Alphen methods, are closely identified with an object of study. Others, like neutron scattering, are very broad and one hardly knows whether they belong to physics, chemistry or engineering.

In the search for new effects or in the isolation of familiar ones the solid state physicist has gone to great extremes. High pressures, low temperatures, high magnetic fields; all define frontiers of his explorations. Above all, high purity has been the recipe for success. Today's great temples of solid state science, the fabrication laboratories of the semiconductor industry, attended by their white-robed Vestal Virgins, are among the cleanest places on Earth. On the other hand, materials science recognises the complicated character and composition of most practically useful materials and the necessity for merely phenomenological methods, *faute de mieux*, in describing them. The conventional solid state physicist's tastes have recently included complexity (in certain refined forms, such as that of the simplest glasses) but he has some way to go before he has much to say about a common brick!

The changing course of science is not at all clear as it happens. Even on a yearly time-scale its movement is almost imperceptible, except for the sudden appearance and often rapid growth of new shoots. On the other hand, over a decade, its movement is clear enough, and can be documented by, for example, plotting the numbers of research students supported by the Science and Engineering Research Council in universities as in figure 5. Solid state science is new enough that it does not yet appear as a separate classification, but it would contain the lion's share of 'mainstream' physics after nuclear and space physics have been excluded. After the growth period of the 1960s, the total numbers of mainstream physics and materials studies have remained roughly constant. The steady shift over the period from physics to materials studies reflects an important trend towards making physics relevant to industry. The proportion of nuclear physics has remained unchanged. Chemistry has followed a similar pattern, although biology has grown substantially over the period.

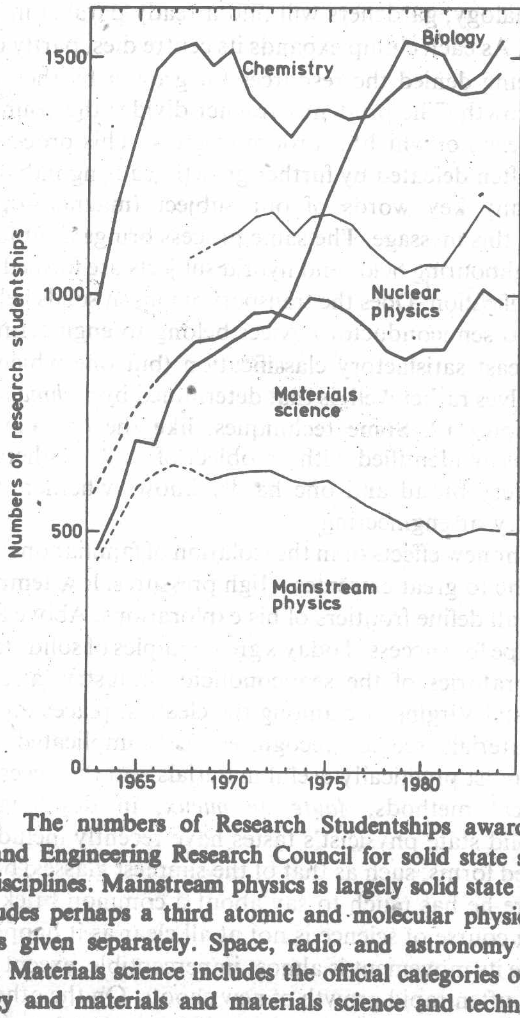

Figure 5 The numbers of Research Studentships awarded by the Science and Engineering Research Council for solid state science and related disciplines. Mainstream physics is largely solid state physics but also includes perhaps a third atomic and molecular physics. Nuclear physics is given separately. Space, radio and astronomy have been excluded. Materials science includes the official categories of materials, metallurgy and materials and materials science and technology. The dashed lines are estimates of the numbers made by interpolation when the classification system used by the Research Council was changed.

How is the content of solid state physics itself changing over the years? Figure 6 shows the numbers of papers indexed in the solid state physics journals *J. Phys. C* (*Solid State Physics*) and *J. Phys. F* (*Metal Physics*), according to the standard *Physics Abstracts* classification scheme over the last dozen years. It is interesting that these show a steady growth over the period, despite the steady numbers of research students—physics is evidently doing its share in raising productivity. The subjects underlying our understanding of metals and semiconductors, for example electron states and electron

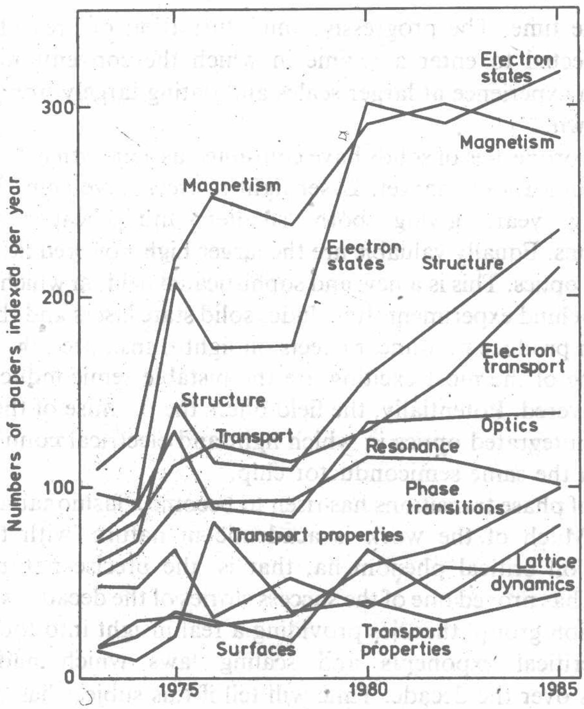

Figure 6 The numbers of papers indexed in the solid state science related journals *J. Phys. C* (*Solid State Physics*) and *J. Phys. F* (*Metal Physics*). The subjects are classified according to the *Physics Abstracts* list illustrated in figure 4. Subjects not rated over 50 during the period are not shown.

transport, continue to grow rapidly. While the calculation of electron energy levels in perfect crystals, the subject of 'band theory', may now be regarded as unexciting, several of its applications, for example the calculations of total energies and hence the prediction of structure, are at a very interesting stage. Partly because simple one-electron theories have worked much better than expected, we now stand on the brink of an era in which reliable calculations can be made on a variety of complex materials for the first time. The consequences of this will be deep and wide, since there are whole areas of the solid state, such as the study of interfaces, where experimental probes are inadequate, and theory may leap-frog ahead of experiment with the help of supercomputers.

Semiconductor device technology continues to stimulate solid state research both intellectually and financially. One might think that by now the emphasis would be very much on the applied side, but the pace of technological advance is such that it is making fresh demands on fundamental physics all the time. The progressive miniaturisation of present devices is currently expected to enter a regime in which the conventional wisdom, acquired from experience at larger scales and dating largely from the 1930s, will break down.

The optical properties of solids have continued as a growth field stimulated by the communications market. Laser light sources have come better with every passing year, giving both smaller and cheaper lasers for communications. Equally valuable are the larger high-powered lasers suitable for non-linear optics. This is a new and sophisticated field, in which theory has often lagged behind experiment. It includes solid state lasers and those special crystals which produce non-linear effects on light transmitted through them. Of these, some of the most exciting are the bistable semiconductor devices recently discovered. Potentially, the field offers the promise of the necessary materials for integrated optics in which light and electrical connections will coexist within the same semiconductor chip.

The study of phase transitions has risen to become a fashionable topic over the decade. Much of the work is academic in nature, with the interest concentrated on critical phenomena, that is, the precise nature of phase transitions. It has proved one of the success stories of the decade, with the new 'renormalisation group' theories providing a real insight into the previously mysterious critical exponents and scaling laws which had occupied experimenters over the decade. Time will tell if this subject has now run its course. It is perfectly desirable and natural that subjects grow under the promise of new understanding that can bring together experimental measurements, and then wither as that understanding is found and applied, eventually reaching that body of accepted knowledge enshrined in the standard texts. Lattice dynamics provides a classic example. It represented a large fraction of the effort in solid state physics at the start of our graph around 1973, yet the 'phonons' of the theory proved easy to measure by neutron inelastic scattering and vibrational spectroscopy became a standard technique of solid state physics. In this rather reduced rôle it continued to contribute to other fields such as surface studies and phase transitions during the decade.

Magnetism has been one of the strongest fields throughout the period. It would be tempting to assert that this has been promoted by the applications in recording and storage media, but in the UK it would be closer to the truth to say that it had been stimulated by theoretical interest in phase transitions and electronic structure. Its future seems assured while so many of its major problems remain unsolved. For example, the magnetism of even a simple transition metal like iron has not succumbed to any simple explanation, and is indeed the subject of just as much effort, both from theory and experiment, as it was a decade ago.

If all of this has a common theme, it is surely to be found in the aspect of solid state science which was stressed in our first classification, that of structure, emphasised in Chapter 2. It may be argued that the invention of the x-ray diffraction technique constituted the very birth of our subject, yet it still holds great fascination for many. The Nobel Prize for Chemistry in 1985 was given for the refinement of the technique of solving structures by direct methods, by Karl and Hauptman, as described in Chapter 12. This, the eventual fulfilment of an old dream (an impossible dream, according to Bragg) makes an interesting contrast with Von Klitzing's Physics Prize of the same year. The latter also related to the solid state, but his work on the Quantum Hall Effect was a total surprise, a sudden flash of brilliance, reminding us that young men will always find new things . . . .

In addition to the classic method of diffraction, we now possess a versatile armoury of new structural probes for special purposes. Many of these relate to the new field of surface science.

Structure is, in fact, often the key to our understanding, and structural studies are rising to become another of the major areas. This is largely caused by the newer techniques being developed over the period, such as neutron and electron diffraction. New surface techniques, many using synchrotron radiation, have caused a large growth in surface and interface studies over the decade, parallelling the development of bulk property measurement over the period from 1920 to 1970. The development of the field has been dominated by the steady improvement in the basic experimental methods, such as low energy electron diffraction, extended X-ray absorption fine structure and Auger spectroscopy from ion bombardment, all combining exciting possibilities with deplorable acronyms. From the applied side comes the general motivation of the desirability of a better understanding of catalysis. Physics and Chemistry are therefore interwoven throughout much of surface physics. Even the physicist wanting to study pure surfaces has to be expert in the removal of surface adsorbates. The subject will surely further expand as the experimental techniques are refined still further

THE BOOK

The present volume, which attempts to encompass some of these diverse topics, arose out of discussions of the Solid State Subcommittee of The Institute of Physics. As editors, we were confronted with a difficult task in selecting what was to be covered. No single volume of this size can really represent the whole discipline. For further reading, we would recommend *The Beginnings of Solid State Physics* (London: Royal Society, 1980). Also recommended are Cotterill's *Cambridge Guide to the Material World* (Cambridge: Cambridge University Press, 1985), Braun and MacDonald's *Revolution in Miniature* (Cambridge: Cambridge University Press, 1982). We all await with interest whatever emerges from the International Project on the History of Solid State Physics.

We hope that undergraduates, in particular, will in future be given more of a historical perspective in their studies and realise that the knowledge we possess today is the product of a long process and a wide community of scientists. The intractable and inscrutable solid has not yielded easily to the scientific method but it is at last within our power to shape, control and understand. When we realise how long this has been awaited and how recently it has been achieved, it becomes clear that we have only begun to explore the consequences.

Denis Weaire
Colin Windsor
June 1986

Contents