acta phys. slov. 31. (1981), No. 2—3

PERSPECTIVES IN THE MAGNETISM OF SOLIDS[1]

S. KRUPIČKA*, Prague

Based on recent discussions on trends and future prospects in magnetism an outline is given concerning topics where the most important progress may be expected in experimental technique, physical insight and technical applications.

ПЕРСПЕКТИВЫ РАЗВИТИЯ МАГНЕТИЗМА ТВЕРДЫХ ТЕЛ

На основе дискуссий последнего времени, посвященных направлениям и перспективам развития магнетизма, в работе приводится обзор развития тех областей магнетизма, где в будущем ожидается наибольший прогресс с точки зрения экспериментальной тецхники, физического понимания и технических применений.

I. INTRODUCTION

There is probably no doubt about the importance of the contribution of magnetism to the modern solid state physics and, also, to technical progress in many branches: the 100 years'history of both electric steels, particularly sheets, and permanent magnets is a good example; the invention of ferrites and their wide use in the 50's and 60's in communication and radio engineering, microwave technique, memories for computers etc. may be compared with the impact of semiconductor devices of that period; many concepts now used in solid state physics and elsewhere arose in connection with studies of magnetism and the magnetic properties of solids — the many-body approach (introduced in connection with spin waves), spin correlations, phase transitions, magnetic symmetries and the necessity to combine them with the usual crystal symmetry operations to obtain the full insight into the symmetry of magnetic crystals, etc. Moreover, many basically magnetic experimental techniques, including classical magnetic suscepti-

* Institute of Physics, Czechoslovak Academy of Sciences, Na Slovance 2, CS-180 40 PRAGUE.
[1] Invited paper presented at the 6th Conference on Magnetism in Košice, September 2—5, 1980

bility measurements, resonance methods (EPR, NMR, Mössbauer) and possibly others are being widely used in various fields of science, research and technical praxis. More detailed discussions about the historic role of magnetism may be found, e.g., in retrospective reviews [1—4].

All this has established magnetism as an attractive and fairly extended field of contemporary solid state physics with a rather large counterpart in applied science and various technologies, whose progress is shown beyond doubt every year at least at two big conferences with about 1000 participants and at a great number of smaller ones of regional or topical character. The aim of this introductory paper is to determine whether this field will remain important also in the future and which parts of magnetism may become particularly attractive during the next years. There have been several high level discussions about this problem just recently [5—7] and have been widely employed here.

II. NEW MAGNETICS AND NEW TECHNOLOGIES

Much of the recent work in magnetism has been connected with discoveries and preparation of new magnetic substances and devoted to the study of their magnetic properties. In fact, the observation of many new magnetic phenomena was only enabled by preparing new materials. Although the number of ways in which it is possible to combine the elements possessing a partly filled *d* or *f* atomic shell with other elements of the periodic system would seem inexhaustible, systematic work during the past few years has limited the real new possibilities as regards the crystalline form and traditional ways of preparation. There are, of course still some promising areas: Compounds and alloys containing 4*f* and 5*f* metals, hydrogenized magnetic metals. More often though, to get new substances we have to proceed to more-component systems — solid solutions or alloys — and the probability of discovering something dramatically new is becoming small. On the other hand many new possibilities are still being offered by amorphous magnetics. The relevant technologies — rapid quenching of the melt, evaporation, sputtering or electrolytic deposition of thin layers on a cool substrate, chemical transport deposition — are still in progress and their future development will enable to prepare new kinds of amorphous magnetics. Let us emphasize that not only does the amorphous state represent a novelty even with a known substance, there also exists the possibility to prepare materials not existing in the crystalline form. The liquid phase epitaxy, getting important particularly in connection with bubble technology, has brought a new quality into the magnetic studies that have not been fully exploited yet. But perhaps the (epitaxial) deposition by molecular beams seems to be the most promissing. It will represent a further step towards submicron and atomic-scale technology; the production of new, synthetic structures prepared

by a controlled atomic layer deposition (modulated structures, composite films, sandwiches, etc.) should then be accessible.

III. EXPERIMENTAL METHODS

It is not possible to expect any important progress in physics without developing new experimental techniques and methods or improving them at least.

The magnetic field is beyond dispute the basic tool for research in magnetism and the tendency to using higher and higher fields has accompanied it during the whole course of its development. The present status and prospective values are as follows [8]

stationary superconducting 15 T → 20 T → (50 T?)
hybrid 30 T → 45 T → 60 T → 75 T
quasistatic (pulse ~ 100 ms) 40 T → 50 (75) T → (100 T?)
pulse fields (~ 1 ms, nondestructive) 75 T (50 µs) → 100 T (0.2 ms) → → 250 T (? ns)
short pulse (destructive) 120 ÷ 300 T → 2500 T (~ 100 ms).

The construction of superconducting magnets for fields above 20 T needs new superconductors with correspondingly high critical fields. As the cost increases very rapidly with every additional Tesla, the hybrid magnets seem to be a more practical solution for fields above 30 T. The measurements in pulse fields are now frequently made up to 40 to 50 T depending on the pulse duration. Recently fields up to 100 T, $\tau = 0.18$ ms have been reported with a model many-layer coil [9]. Subjects suitable for high magnetic field research are, e.g.: critical and multicritical behaviour, magnetically induced phase transitions, magnetic phase diagrams, magnetic state and excitations of itinerant magnets, NMR with a very high resolution.

Sometimes just opposite demands are to be met: extremely weak fields, their detection and measurements are required, particularly in connection with biological objects as the human brain or heart [10, 11]. Here superconducting quantum magnetometers (SQUID's) are prospective detectors with an extreme sensitivity and modern very soft magnetic materials like metallic glasses may be used in magnetic shielding.

Another fundamental technique which will be improved in the future is neutron scattering, both elastic and inelastic. New sources of neutrons with higher (epithermal) and low (cool, ultracool) energies are being developed to yield the possibility either to study higher excitation (e.g Stoner excitations in itinerant ferromagnets) or, on the other hand, to use neutrons for surface investigation. Moreover, new techniques and methods, e.g., spin echo, promissing an increase in sensitivity are being developed or proposed.

Among special methods designed for electron spin polarization studies, particularly in connection with surface magnetism, photoemission (using mostly synchrotron radiation) and tunnelling experiments besides newly developed electron capture spectroscopy (ECS) [7] and polarized low energy electron diffraction (PLEED) [12] have to be mentioned.

Last but not least optical methods, Brillouin and Raman scattering, magnetooptic spectroscopy, etc., have played an indreasing role during the last years in studying electronic levels and excitations in magnetic systems and this trend will probably continue.

IV. PHYSICAL PROBLEMS

An old and perhaps the most fundamental problem of magnetism of solids is the electronic structure and its relation to magnetic properties. But has been only recently that an important progress has been made towards solving it both in theory and experiment. The local spin density method (see, e.g., the paper by P. Novák in this issue) combined with modern large computers is able to give a reasonable approach to the electron correlation problem and hence — for the first time in history — to determine the electronic structure of solids and all quantities depending on it (including magnetic moments and other quantities important for magnetics) on the basis of first principles. The main progress is expected in metallic magnetics but also magnetic surfaces, surface and local states, clusters (with possible applications to disordered and amorphous systems) and some other special type of materials, e.g., mixed valency compounds, are likely to profit from this development. It turned out that the present theory yields very good results for the ground state but the problem of excited states seems to be still open because there are still severe discrepancies between theory and experiment [6] stimulating new progress in the theory. From the experimental techniques which contribute to our knowledge in the field of electronic structure let us mention electron photoemission, optical and X-ray spectroscopy, and inelastic neutron scattering. Note that a detailed understanding of the relations between structure — both crystallographic and electronic — and magnetic properties will be of great importance and help in finding and designing new magnetic materials and in optimizing their properties.

The field which awaits further studies are excitations of magnetic systems including their interactions with other excitations in solids (phonons, polarons, excitons, etc.) and with the electromagnetic field. Both problems on the atomic level and effects on the level of s.c. micromagnetism are to be solved. Very little is known about the dynamics of magnetic systems exceeding the linear approximation; the soliton-like solutions of the sine-Gordon type equation are being examined presently, particularly in two cases: domain walls dynamics [13] and high temperature non-linear excitations in quasi one-dimensional ferromagnets [14].

The solution of the latter problem for 2 and 3 dimensional systems is, however, fully a matter of the future. This problem of nonlinear excitations is also closely related to critical fluctuations and phase transitions. On the other hand, we have not sufficient knowledge of the microscopic mechanisms of magnetooptic phenomena and the nonlinear optical and magnetooptical properties in various parts of the spectrum are a practically untouched field, too.

Quite new possibilities arise in the study of magnetic effects on surfaces and interfaces. Two kinds of problems are involved (1) the specific manifestation of the surface magnetism (magnetic arrangement, surface modes and their excitement, etc.) and (2) the influence of the surface and its state upon the bulk properties (sheets and layers, effect on the domain structure). In connection with what has been said above about new methods of preparing synthetic composite layered structures and new possibilities of calculating electronic structure quite a revolutionary progress may be expected.

Finally a lot of unsolved physical problems may be found in disordered magnetic systems — disordered alloys, spin glasses and amourphous magnetics. In all these cases, e.g., the theory is not yet adequate; the character of the transition to the spin-glass state is not clear, very little is known about the time dependence of spin correlations in the spin-glass systems. The structural relaxation in amorphous materials and its relation to magnetic properties is quite a problem and only recently some attempts have been made [15] at passing beyond the mere radial distribution function when characterizing the amorphous state. The progress along this line could help to overcome the fundamental difficulty in calculating the electronic structure of amorphous magnetics. Let us add that from the experimentalist's point of view besides classical magnetic studies also neutron diffraction, Mössbauer effect and resonance experiments seem to be promissing in connection with disordered magnetic systems.

V. APLICATIONS

The classical field of applications are the soft and hard magnetic materials. The spectrum of materials used is very broad in order to meet the demand for a big variety of technical requirements. In the course of time these materials undergo a continuous process of improvements and innovations. The progress achieved is big and important. As an example let us mention the permanent magnet materials: their quality as expressed by the energy product $(BH)_{max}$ has been growing exponentially with time for about 100 years, being doubled within a period of 12 years and reaching ≈ 240 kJ/m^3 at present. By extrapolating this trend the theoretical limit will have been reached in about 15 to 25 years [3]! But not only this trend presently represented by R—Co based intermetallics will be determining in future. The worldover shortcomings in cobalt make a demand on researchers to develop permanent magnets which would contain no Co or at least less than many materials used; the Mn—Al based alloys and Co poor Fe—Cr—Co alloys are possible solutions to meet these demands.

The development in the field of soft magnetic materials may be in the near future dramatically influenced by the discovery and rapid development of amorphous ferromagnetic alloys (metallic glasses). Their advantages are as follows: zero magnetocrystalline anisotropy, higher electical resistivity, easy production of thin ribbons (0.003 to 0.005 cm thick) and, hence, considerable reduction of losses — even at relatively high frequency. Moreover, a reduction of the production costs is expected. Two lines of research are pursued: (1) high saturation materials (presently represented by Fe—B based "metglas" ribbons to substitute the high-quality grain oriented Fe—3.2%Si sheets at least in some power applications, and (2) ultra soft materials ($\lambda_s = 0$) for special applications. In particular, the realization of the first project would be economically very important, taking into account the enormous quantity of transformer-steel produced nowadays: the total energy loss of the installed transformers and machines is estimated [3] to be 3×10^{10} kWh per year so that the expected 50 % reduction of the losses in metglass materials even in partial application would bring a considerable contribution to the energy problem.

The application of magnetism and magnetic materials, whose importance is rapidly increasing, is the magnetic separation. The progress has been enabled by introducing the s. c. high gradient magnetic separation (HGMS) in the 70's which can be used even for separation of small paramagnetic or diamagnetic particles [16]. Exhausting many first quality natural resources and the necessity of exploitation of the poor ones or recycling the materials, the problem of separation of various constituents becomes to be of primary importance. For physicists there are still open problems — both theoretical and experimental ones — mainly as regards the optimalization of separators.

Quite a new era in applied magnetism has started by the bubble memories. The principal novelty of this invention consists in the fact that in this type of memories the magnetic domains are employed for information storage individually, unlike all other applications of magnetics where only the macroscopic behaviour is exploited determined by the integral (or averaged) properties of many microscopic regions (domains, grains). Thus proceeding to a direct application of micromagnetic domains a qualitative jump has been made towards the microminiaturization of magnetic devices. At present the bubble domains are used in the form of shift registers with bubbles of a diameter of 2 to 6 μm and information storage density $\sim 10^6/cm^2$. As carriers the single-crystal garnet films epitaxially grown on GGG substrates by the LPE method are used. The next goal should be the decrease of the bubble diameter and the increase of their mobility by designing new garnet or other materials for bubble layers, including the development of an adequate micron or submicron overlayer technology. A further perspective may be seen in empolying the whole close packed bubble lattice and to replace the shift registers by wall-state or other local coding. It may be expected that the present production of bubble memories means only the beginning of a new era in employing domains and micromagnetic effects.

A further step towards submicron technology in magnetic devices will be the future exploitation of magnetic surface phenomena including the synthetic layer structures (see above). Even though the perspectives are rather long terms ones, many people are already engaged in studying the possible applications: new ultrafast circuits and memories, spin junctions, sandwiches combining ferromagnetic and superconducting layers, etc. Also production and employment of regularly dispersed small magnetic particles and contribution to a better understanding and applications of catalysis should be mentioned here. Besides, there are some further reserves for future applications: magnetic semiconductors, magnetics that at the same time exhibit ferroelectric behaviour, magnetooptic devices which could become relevant in connection with a further development of optoelectronics, etc. Also the applications of magnetism in biology and medicine seem to be a prospective field.

REFERENCES

[1] Anderson, P. W.: J. Appl. Phys. *50* (1979), 7281.

[2] Rado, G. T.: J. Appl. Phys. *50* (1979), 7285.

[3] Jacobs, I. S.: J. Appl. Phys. *50* (1979), 7294.

[4] Krupička, S.: J. Magnetism and Magnet. Mat. *19* (1980), 88.

[5] Zinn, W., Methfessel, S.: J. Magnetism and Magn. Mat. *15—18* (1980), 1588.

[6] Eastman, D. E., Janak, J. F., Wiliams, A. R., Coleman, R. V., Wendin, G.: J. Appl. Phys. *50* (1979), 7423.

[7] Freeman, A. J.: J. Magnetism and Magn. Mat. *15—18* (1980), 1070.

[8] Keller, S. P.: J. Appl. Phys. *50* (1979), 7757.

[9] Date, M., Motokawa, M., Okuda, K., Hori, H., Mollymoto, H., Sakakibara, T.: J. Magnetism and Magn. Mat. *15—18* (1980), 1559.

[10] Williamson, S. J., Kaufman, L.: J. Magnetism and Magn. Mat. *15—18* (1980), 1548.

[11] Odehnal, M., Petříček, V.: Czech J. Phys. *A 26* (1976), 254.

[12] Wang, G. C., Dunlap, B. I., Celotta, R. J., Pierce, D. T.: Phys. Rev. Let. *42* (1979), 1349.

[13] Borovik, A. S., Maslov, K. V.: Fiz. Nizk. Temp. *4* (1978), 94.

[14] Steiner, M.: J. Appl. Phys. *50* (1979), 7395.

[15] Egami, T., Maeda, K., Vítek, V.: Phil. Mag. (1980).

[16] Friedlander, F. J., Takayasu, M., Nakano, T., Kelland, D. R.: J. Magnetism and Magn. Mat. *15—18* (1980), 1555.

Received October 20th, 1980