



Shown above in Prague are Jan Tauc of the Czechoslovakian Institute of Physics and W. C. Dunlap, the author of the present article. In the background is the Moldau.

Semiconductor Research in the USSR

By W. Crawford Dunlap, Jr

THE trip described in the present report was an experiment in determining to what extent a private American tourist could visit scientific establishments in the USSR. The author had no official sponsorship by either the Soviet or the American governments, nor any official mission or invitation.

The primary motivation for going ahead with such a trip consisted of a personal letter to the author by Academician A. F. Joffe, director of the Institute of Semiconductors, in Leningrad. This letter, in response to a previous short inquiry about the possibilities of making such a trip, contained an invitation to visit Prof. Joffe at his laboratory and to discuss there recent developments in semiconductors. Beyond this the author had hopes rather than plans.

The main centers known to the author for semiconductor work are Leningrad, Kiev, Kharkov, and Moscow. An Intourist itinerary has to be chosen before a visa can be granted to a tourist. In the present case, "Tour No. 15" was selected, primarily because it begins in Leningrad and is the only Intourist itinerary to start there and to include all four centers. Besides these four cities, the tour includes a trip through southern Russia, the Crimea, the Black Sea, and the Caucasus.

By the time a decision had been made to go ahead with the trip, the season had already advanced well into the fall, so that a chilly tour was in prospect. The author left the United States by plane on November 5, and, after a short stop in Paris for a visit with Prof. Pierre Aigrain at the Ecole Normale Supérieure, arrived in Leningrad at midnight, November 11.

Leningrad

AFTER being established at the Intourist hotel, the Astoria, I had a good night's sleep, and awoke to find Leningrad cold but sunny. After breakfast I took

An account of a trip made last year by an American physicist to Soviet Russia, during which he visited several of the important semiconductor research institutes and interviewed, among others, Academicians Joffe, Kapitza, and Landau. Visits were also made to semiconductor research centers in Paris, Prague, Erlangen, Pretzfeld, and Zurich. The author is supervisor of solid-state research at the Bendix Aviation Research Laboratories in Detroit.

a walk through the streets in the vicinity of the hotel. Very few cars were about, but the sidewalks were full of Russians hurrying to their work. Russian crowds have a special character, which seems to derive from the dark uniformity of their clothes. The men wear the same style black overcoats and black hats, while dark coats with bandannas are the hallmarks of the women. The scattering of stylish and brightly colored ladies' overcoats seems merely to accent the drabness of the clothing worn by others.

At the hotel after this walk, I met Victor, who was to be my guide and interpreter in Leningrad. Although interpreters generally go with the tourist from city to city, there appears to be no obligation for one to keep the interpreter in the cities, and many times I dismissed the interpreter for a morning or an afternoon while I strolled about the city for a look at the stores.

Victor, at my request, called the Institute of Semiconductors to arrange a meeting, and was told that Prof. Joffe would like to see me at 4 o'clock that afternoon. In the meantime, we toured through the city and I took a number of color photographs of the many impressive buildings and scenes, some of which date back to the time of Peter the Great.

Just before four o'clock our black Zim limousine pulled up to the front of the Institute of Semiconductors at 187 Kutuzova. The building is the former French embassy from the days when Leningrad was the capital of Russia, and Joffe's Institute had taken it over only a few months previously. The building, in a light blue stucco, fronts directly on the Neva River, and faces the Medical Institute, the Peter and Paul palace erected by Peter, and several other historic Leningrad landmarks.

We found Prof. Joffe in his office, a large, rather dimly lit room, having numerous bookcases, and a set of handsomely built tables and chairs. Prof. Joffe is

now 78, and has resided in Leningrad for 60 years. He is florid in complexion, and is bald on top with a spray of white hair going out on all sides. He reminded me very much of some of the pictures of Albert Einstein in his later years. Professor Joffe is a very courtly, courteous person to talk to, and all our conversations were most enjoyable to me. During one of the visits I prevailed upon him for a color photograph, shown in black and white.

The first hour of this visit was devoted to discussions of the general program of Professor Joffe's Institute. He has about 200 people in this Institute, of whom about 50 are of professional caliber. The greater part of the work is devoted to research on various semiconducting compounds, although much work is done on some development projects. The Institute is especially famous for the work done on new thermoelectric materials and devices. Cooling by the Peltier effect has formed one of the chief projects of the group, and this work is now known world-wide. By passing current through a $p-n$ junction, or through a metal-metal contact, heat can be released or absorbed, depending upon the direction of the current. By proper choice of the materials, Joffe has now been able to reduce the temperature in the vicinity of the junction by about 90°C .

He displayed to me a number of demonstration devices illustrating the practical applications of the effects. One of these was a kerosene lamp operated power source for a home receiver. This arrangement delivers 3 watts of electrical power at a voltage of 150 volts, sufficient to operate a small two- or three-tube set. The outfit is now being manufactured for use in remote regions having no electricity.

Another similar application and even more important potentially was the home refrigerator. This 3- to 4-cubic-foot cabinet has a temperature 30°C below the surroundings. The current passes through a set of junctions mounted on the back, with cooling vanes extending from the back to remove the heat liberated at the second junctions. The cool junctions are in contact with a metal plate extending into the cabinet. No provision for making ice is available, and in warm climates the temperature obtainable would be well above the freezing point. Dr. Joffe indicated that this cooler should be competitive with those operated by compressors, although nothing he said convinced me that he had any adequate idea of the cost of making the cabinet. The cost of the elements, he indicated, should not be over a dollar or two, but whether this really included the various items involved in refining and preparing the elements is hard to say.

Other applications included a cold trap for vacuum systems, a dew-point meter using a silvered surface cooled by the Peltier effect to form the dew, and a microtome sample holder, with which tissues or other material could be cooled or frozen so as to improve the cutting process and to minimize thermal damage. This arrangement, as did some of the others, has auxiliary water cooling. Since water temperature in Leningrad for much of the year is only a few degrees C, the tempera-

A. F. Joffe, director of the Institute of Semiconductors in Leningrad, as he was photographed in his office by the author.



Peter Kapitza (at right), director of the Vavilov Institute of Physical Problems in Moscow, with the associate director of his laboratory, Mr. Malkov.



ture attainable with reasonable junction efficiency may be well below -30°C .

Another interesting instrument application was the thermocouple cold junction. This consists of a Peltier cooling junction and a small water cell. The freezing of the water interrupts the cooling process, and thus the cell can be maintained at exactly 0°C to within about 0.1°C . This small unit thus makes a convenient reference junction for thermocouple measurement work.

The remainder of the applications were variations of the above including a variety of thermostats and sample holders for temperatures both above and below room temperature.

Naturally, much of the research work at the Institute is devoted to those properties of semiconductors that have a bearing on the thermoelectric and Peltier effects. Much attention has been given to means for improving the "figure of merit" for the Peltier effect. This requires minimizing the thermal conductivity with little or no interference with resistivity or mobility. One of the successful materials is a mixture of lead telluride and lead selenide. This mixture exhibits a decreasing thermal conductivity with increasing proportions of either in the other, the minimum being at about 50 percent. The



The building of the Academy of Sciences of the USSR, Bolshaya Kaluzhskaya, Moscow.

surprising thing is that the mobility for carriers in these mixtures varies but little with mixing proportion, and may even be slightly higher for the mixture than for the pure compounds. Much work is also being done at the Institute on various mixtures of bismuth and arsenic tellurides and selenides. Little definite information as to the exact materials and compositions yielding the greatest thermoelectric efficiencies could be elicited.

During the conversation with Prof. Joffe there was also much discussion of the state of the semiconductor field as a whole, and particularly of semiconductor theory. Joffe feels that theory now is hamstrung by having been derived for semiconductors from basic theory that actually applies to metals only. He has but little faith in the band theory, for example, and relies in his thinking to a great extent on conduction as electron transfer between atoms. On a more formal basis, he feels that a new approach to semiconductor theory based perhaps upon the tight binding approximation is needed. There are two theoretical groups in the Institute, one headed by Dr. Anselm, the other by Dr. Samoilovitch. Dr. Anselm's group is working on problems tractable by present methods. Dr. Samoilovitch's group is tackling the problem of revolutionizing semiconductor theory by replacing present band theory with a more suitable one. I gathered that the Leningrad group was much influenced by Dr. Pekar at Kiev and his studies of many-electron theories.

Prof. Joffe is probably the "dean" of Soviet scientists. He is the oldest Academician in point of service, if not also of age, having been elected to the Academy in 1920. He is unique also in having founded more Academy institutes and having had more students and protégés become Academicians than any other member of the Academy. Having been responsible for founding 15 institutes of the Academy, he was at the present time engaged in founding a 16th, an Institute of Agricultural Physics in Leningrad. He expected to spend alternate days at the new institute and the Institute of Semiconductors for at least six months before returning to full-time service at the Institute of Semiconductors. On two of the three days that I talked with him he had undertaken a special trip back from the other institute in the chauffeured limousine furnished him continuously by the government.

These discussions were all held in English. Prof. Joffe spent a year in the United States in 1927, lecturing at MIT and the University of California. He in-

dicated that until last year he had no further opportunity to visit English-speaking countries, and little opportunity to speak English.

After the office discussions we took a quick tour through five or six of the laboratories. The first one visited was that of Prof. Joffe's wife and collaborator, A. V. Joffe. She is a pleasant middle-aged lady who was in the middle of an experiment in her small laboratory room when we arrived. After introductions and a few pleasantries we left her and visited two other laboratories also staffed by middle-aged lady physicists, Mrs. Mochan and Mrs. Devjatкова.

We went into the discussion of the apparatus and the experimental results in considerable detail. There was little reticence to discuss scientific results, and many of the data discussed were of recent date and unpublished. Mrs. Mochan had for example been studying the thermal conductivity of *n*- and *p*-type germanium, and had apparently come across a real difference in the conductivity according to the type of carrier. The difference was of about 10 percent and applied for the whole temperature range studied, from liquid air to room temperature. Transport of ionization energy as a source of the effect has been ruled out, and it appears that differences in structure, dislocation, and defect density, depending upon the nature of the impurities, may be responsible. Since several of the samples studied had been converted from *n*-type to *p*-type by thermal quenching, the possibility of structure changes induced by thermal shock must be included.

In this same visit we visited the laboratory of C. Stil'bans, one of the leading experimentalists in Prof. Joffe's laboratory. Stil'bans has been investigating scattering in lead sulfides and tellurides, particularly attempting to resolve the contributions to temperature dependent scattering that derive from (a) the change of carrier velocity with temperature and (b) the change of the lattice vibrations themselves with temperature. The first was approached with samples of various degrees of degeneracy, so that the conducting electrons had various velocities determined by the degeneracy; the second question was approached by study of the mobility at high temperatures, rather than the low temperatures used for the first set of samples.

The second day I spent at the Institute was devoted to discussions with the groups of B. I. Boltaks and V. P. Juse. Boltaks has done considerable work in the study of semiconducting compounds, beginning with Mg_2Sn , and has also worked a great deal on the study of diffusion and electrical activity in germanium. This was a group discussion with Boltaks and ten or twelve of his student associates gathered about his desk. Since Boltaks does not speak English, we were at greater difficulties than with the people working directly with Joffe, who is a wonderful interpreter.

Boltaks' associates were primarily interested in the effects of various impurities in germanium. They are working directly and actively in following up the work I have done on gold and other elements in germanium. They feel, and probably correctly, that the whole story

is not yet known regarding the nature of the amphoteric impurity center that can have donor or acceptor character. When gold acts as a donor, for example, must the atom be in an interstitial site, or can it be substitutional? Outside of expressing the opinion, based on some evidence, that the donor center was the same as the acceptor, and probably substitutional, I could only suggest that there was an excellent opportunity for them to make contributions by clarifying these problems themselves.

Besides supervising a group at Joffe's Institute, Boltaks is also in charge of a similar group at the Physicotechnical Institute at Leningrad. However, because of the absence of the director, he found it impossible to allow me to visit this establishment. Other well-known people here are Kolomiets and Nasledov.

The third group in the Institute of Semiconductors whose laboratories I visited was that of V. P. Juse, well known for his pioneering work on cuprous oxide and other semiconductors in the 1930's. At the present time Dr. Juse is in charge of a group mainly engaged in studies of galvanomagnetic effects, and in the development of choppers and modulators and other devices utilizing the Hall effect, magnetoresistance, and related effects. He showed me several modulators in the experimental stage. We also discussed with Mr. Bogomolov their recently developed harmonic analyzer based on the Hall effect. If a complex wave form is impressed on a crystal in the form of crystal current, and an ac field of constant amplitude and variable frequency is used for the magnetic field, the Hall output voltage is determined by the magnitude of the Fourier component of the complex wave form at the frequency of the magnetic field. The output is read on a dc galvanometer. Although the authors of the work were enthusiastic about its possibilities, they stated that the instrument is still in an early stage of development and is not yet ready for commercial production.

After having understood from Prof. Joffe that he would not be available during my last day in Leningrad I was surprised the next morning at the hotel to learn that Prof. Joffe would make a trip back from his new Institute and would like to see me again at 4 o'clock that afternoon. It developed when we started talking again that he was interested in an objective evaluation of his Institute, and this led into a rather long discussion of the state of semiconductor research, what the next area of development might be and should be, and Prof. Joffe was wondering if his Institute was playing its proper role in this development.

I pointed out immediately that as a long-time student of germanium and silicon, my views might be somewhat prejudiced, but that was all right. It seemed to me that the greatest advances in semiconductor science from a quantitative point of view were being made with highly purified germanium. I pointed out the usefulness of this highly developed material for quantitative comparisons of theory and experiment, completely apart from the highly important commercial applications of rectifiers, photocells, and transistors. It de-

veloped that Joffe felt that he was happier and could make his most effective contribution when he was off in an area where not too many people worked. He also felt that so many important qualitative questions could not be answered by the use of monatomic semiconductors, that he was justified in continuing to base his program on the study of such materials as the tellurides, selenides, and sulfides. He reiterated his beliefs that fundamentally what was needed in semiconductors was a complete reformation of the theoretical basis of the subject, starting from the theory of insulators rather than that of metals. Naturally, he was happy that his studies had led to important practical developments in the area of thermoelectric devices, but he expected to continue research in basic subjects as the heart of his program.

Prof. Joffe agreed that the development of the theory and experimental properties of excitons, polarons, and other entities requiring many-electron models for their proper discussion would be among the chief items on the agenda of solid-state research during the next few years. In this matter also he felt that much could be done with compound semiconductors in spite of their relatively poor situation regarding purity, homogeneity, and structural perfection.

My impression of Joffe's Institute in general was that it was a first-class scientific establishment. Led by a man of undeniable stature and personality, it was staffed at all levels by competent enthusiastic people. Their conversations indicated that they had considerable freedom as to how they chose their specific problems and the techniques used to solve them. The laboratories themselves are antiquated, since but little remodeling of the old buildings has been undertaken. The laboratory rooms tend to be rather small, often with no windows and crowded with assistants and helpers. The equipment is of good quality, as far as one can judge from superficial examination. Most of the electrical instruments are Russian made, although some are German and Czechoslovakian. The supply of qualified scientific workers is ample. Boltaks informed me that they had a waiting list of ten qualified scientific people for each prospective opportunity in this Institute. Whether this is general or a reflection of the standing of semiconductors in general and of this Institute in particular is hard to say.

Being an Institute of the Soviet Academy of Science, the Institute of Joffe is administered directly by the Academy. However, Joffe is himself the head of the semiconductor section of the Academy's administrative staff and thus has much to say about the conduct of semiconductor research in the rest of the country as well as having personal responsibility for his own Institute. He is also editor of the *Journal of Technical Physics*, author of several books and many papers, and head of the semiconductor commission of the International Union of Pure and Applied Physics. As we parted I congratulated him on his accomplishments, on his present high level of activity, and wished him many further years of achievement.

Kiev

I ARRIVED by plane in Kiev on a Saturday afternoon, and by the time I had checked into the Intourist hotel it was almost two o'clock. I had previously written to Dr. Palladin, president of the Academy of Sciences, but had left for Russia immediately after. We called the Academy and learned that most Institutes were closed at noon. Shortly after this we learned that they had called Dr. Pekar, who was out of town, and that he would come into town to meet me.

We visited the Presidium of the Ukrainian Academy of Science, which is only a few blocks from the hotel. There we met Dr. Pekar and Dr. Gvidnev who is a metallurgist and a leading Soviet expert on the metallurgy of nonferrous metals, including tin and copper. Gvidnev is a Corresponding Member of the Soviet Academy, while Pekar, a theoretical physicist, is a full Member of the Ukrainian Academy, which nominally is an independent Academy of Science.

We carried on a short discussion of the state of theoretical physics, during which Pekar expounded on some of his ideas, and reviewed some of his previous work, which included a survey of his early work on the theory of rectifiers which was similar to and actually antedated shortly the work of Mott and Schottky. He has also been instrumental in setting up much of the theory of excitons and polarons. In this work he has studied the basic equations of quantum mechanics as applied to solids and has decided that the Hartree-Fock and related formulations are inadequate, particularly for problems and properties of excitons, which cannot well be described by any one electron theory. He has described the contradictions in the present theory in a paper published in 1954. He and many others I talked to feel that American solid-state theorists are unduly influenced by one-electron theories of solids and by the band theories based upon them. I disclaimed the knowledge or authority to attempt a defense of such theories.

Pekar feels that a fundamental change in theory is called for but does not feel that he has yet a good solution to the problem. He and his associates, however, are actively working to this end. Another specific area of present activity is in the study of groups of excitons, which he describes in terms of "exciton waves".

The interview was conducted in a combination of English, German, and Russian. Pekar is learning English, but speaks it rather poorly, and was completely baffled by my rapid and not very clearly enunciated English. It turned out that my German was considerably better than his English, and most of the talking was done in that, with asides and contributions in Russian by the interpreter.

At the end of the interview Pekar asked me if I could stay over in Kiev until Monday, and give a talk on semiconductor work in America at the Institute of Physics. After checking with the Intourist people, it was found that the time schedule for the itinerary could be altered with little difficulty, and I agreed to

stay over. Pekar invited me to give the speech in English, since there were quite a few people studying the language there.

The next morning, Sunday, I got the idea of giving the lecture in Russian. Recalling Pekar's difficulty with my English, I felt that it would undoubtedly be even more difficult for most of the others attending. Hence I thought it might be interesting to work up a speech in Russian, since I had until noon of the following day. Even though my interpreter was slightly ill as the result of a vodka drinking bout he and I had engaged in the previous day, from which he, as a matter of fact, did not recover completely during the whole of the rest of the tour, I roused him out and we spent the next 11 or 12 hours writing out the speech, translating it, transcribing it into large block Russian letters, and practicing accenting and speaking the sentences correctly.

We arrived at the Institute of Physics at the appointed hour the following afternoon. The Institute is in suburban Kiev, in an area where there is new housing going up, and a few older peasant-type houses. The lack of new individual homes in suburban areas is striking in Kiev as in most of Russia. Most new housing is in the form of large apartment buildings, and practically all the individual homes are old and dilapidated. The Institute is a fairly new white building built since the war. It bears many of the marks of the stuffy classical architectural styles that have dominated Russian building since the Revolution. I was not allowed to photograph it.

We were met at the front door by Associate Director Miseluk, himself a well-known semiconductor physicist and one of the first to publish in Russia papers on the conduction properties of germanium. After a short discussion in his office, we went to the lecture hall. It was full to overflowing, not only by staff members of the Institute, but by staff from Kiev State University and by members of the Physicotechnical Institute at Kiev. Here as in most of the other places I visited, it appeared that I was the first American solid-state physicist to have visited the establishment.

The talk went off all right, in spite of a few stumbles over long Russian words. I had a few mental hazards in the text, because the interpreter had warned me that a slight mispronunciation of several of the important words could convert them from innocent scientific terms to pieces of obscenity. Dr. Pekar in his conversation later expressed much surprise that I had given the talk in Russian and added in English, "Your Russian it is bee-yoo-tee-full".

After the talk I agreed to answer questions, which occupied a full three-quarters of an hour. These questions mostly dealt with the properties of germanium, and I could detect here a completely different atmosphere than that in Leningrad, where germanium properties were decidedly of minor interest.

The Kiev Institute has the charter from the Academy to develop the physics and technology of semiconductors, particularly with respect to those materials of im-

portance commercially. Their work is strongly oriented to germanium, and I was told that there was a great deal of development work on germanium devices, and particularly studies on the theory of these devices. Peculiarly enough I was unable to find any evidence of work being done on silicon.

Among the interesting people I met at this meeting and another more private discussion following were K. B. Tolpygo, E. I. Rashba, Prof. Deigen, Prof. Lyachenko, and many others. Tolpygo and Rashba particularly are interested in the theory of $p-n$ junction devices, and in the theory of recombination, trapping, and noise. Pekar is, of course, interested more in basic solid-state theory, as is Prof. Deigen, an expert in the theory of F -centers and similar topics. Again discussion centered on criticism of American approaches to the theory of the solid state. We also discussed the theory of transistors, the dependence of injection efficiency on emitter current, and similar matters. Tolpygo and Rashba impressed me greatly by their knowledge both of American experimental and theoretical work and by their grasp of the basic factors in the theory.

Following this discussion Dr. Miseluk showed the entire group of laboratories in which basic work was done, although I did not see any of the laboratories in which the device work was done. The laboratories were very similar to what one would find in a modern American industrial laboratory, although again the facilities of the building were old-fashioned by modern industrial standards. All the standard experimental techniques were being applied. One laboratory, for example, was devoted to the study of surface states, surface recombination, and lifetime, by use of the Many method and spark photoconductivity.

In another laboratory, that of Prof. Lyachenko, surface properties of given samples of germanium were studied by a great variety of methods, including the Brattain-Bardeen cycling method, the PEM effect, field effect, surface recombination techniques, and many others.

I was also shown the germanium furnace room, in which germanium of 10^{12} impurity centers/cm³ was produced. Like all the other germanium furnaces I saw in Russia, this system was a vacuum system. It was very nicely designed and well built. There was provision for rotation of both crucible and seed, for vibration, and for doping with various elements. Quartz crucibles were used, and the heating was by a resistance method.

My impressions of the Kiev Institute were very much like those at Leningrad. The program there is large, with about one-third of the staff of 400 working directly on germanium and similar materials. The rest are working on dielectrics, electronics, and nuclear physics. The activities range all the way from the most fundamental theory right down to development device activity. The scientists have considerable freedom on their individual projects, although naturally the general program is determined by the Academy of Science in Moscow.

Moscow

AFTER about ten days for an interesting tour through the Black Sea regions and Georgia, I went through Kharkov to Moscow. Tiflis and Kharkov were a disappointment scientifically speaking, since most of the scientists whose names I had been given were in Moscow at a scientific conference. I had the opportunity to visit an agricultural research institute on a state cattle breeding farm, and a large electrical manufacturing plant in or near Kharkov, so that the time there was well spent.

In Moscow, I visited three laboratories, the Physics Department at Moscow State University, the Cryogenics Laboratory, attached to the University, and the Institute of Physical Problems, where I talked to Peter Kapitza and L. D. Landau.

I spent one morning at Moscow State University. I was met there by Prof. C. G. Kalashnikov and V. S. Vavilov, both well known for their semiconductor work. Prof. Kalashnikov is head of the Semiconductor Section of the Physics Department, which has about 5 or 6 faculty members and 20 to 30 graduate students. Among the staff members we met were V. L. Bonch-Bruевич, an outstanding theoretical physicist, and B. G. Alexeeva.

Like all the other physicists I met in Russia, they were extremely cordial, and discussed their programs with great enthusiasm. Prof. Kalashnikov is particularly interested in recombination, and has been studying the effects of various elements on the lifetime in germanium.

In particular, they have just finished a study of the effects of various three-five column elements on the bulk lifetime. The elements studied included bismuth and thallium. A rather strong dependence was found, that could not be accounted for by Shockley-Read theory, since there was a large variation between the various elements. We discussed the discrepancies, and concluded that most likely there was a structure effect associated with the various impurities, either in the form of dislocations or atomic defects, which are known to act as recombination centers, and which could therefore account for the observed effects.

This department was one of the few I saw that was working on silicon. However, this work, being done by J. E. Pokrosky and others, was devoted to the basic method of purifying silane and converting it into silicon by thermal decomposition. The silicon so deposited was found by electrical studies to be intrinsic in resistivity. When pulled crystals were made, the resistivity was only about 100 ohm-cm, p -type. The fact that this was the only silicon activity I came into contact with leads me to believe that Russian effort is going, both in research and development, into work on germanium, and that serious effort on silicon is just beginning.

Vavilov was the only younger physicist I met who had been to the United States. He was here in 1955 as the scientific adviser to an English scientist working on a United Nations project. His travel was restricted to

a small area around New York City, and thus the Bell Laboratories was the only laboratory he was able to visit. He is the son of a famous Russian scientist after whom Kapitza's Institute, the Vavilov Institute of Physical Problems, is named. Young Vavilov is now working on the properties of germanium irradiated by fast neutrons and electrons. He is studying the properties of samples originally doped to various levels by aluminum and arsenic, using electrical and infrared techniques to evaluate the effects particularly of fast neutrons.

In this connection we visited the laboratory where the doping studies were made. We talked with Klaus Thiessen, a West German now doing advanced studies at Moscow University. He was investigating particularly the changes in electrical properties of germanium as a function of added aluminum concentration. He found that about 2×10^{14} atoms/cm³ aluminum had to be added before any observable change in the original conductivity could be observed, even though the donor density of the original material was only about 2×10^{13} . We offered on both sides similar but not identical theories of these effects, in terms of the work of Priest of a few years ago, who felt that traces of oxygen in the system could lead to the chemical combination of acceptor elements in the germanium and thus lead to their removal from electrical activity. Because of the differences in behavior of aluminum in a vacuum of 10^{-5} mm and in pure dry hydrogen, Thiessen concludes that such reactions do take place, but only in the combined presence of both oxygen and hydrogen. As in other laboratories, much of the discussion involved unpublished work as well as aspects that have recently been published.

Another laboratory of considerable interest was that of A. E. Yunovich, a physicist who is doing excellent work on surfaces by means of field effect, surface recombination, and other techniques. He has recently made studies of the high-frequency dependence of the field effect in germanium, in which he has independently discovered the relaxation phenomenon also described by Garrett and Brattain.

After visiting the experimental laboratories, I talked at some length with Bonch-Bruevich, who is much interested in the problem of trapping, recombination, and the effects of various impurities on germanium. He is thinking of doing some work on the ionization energies of impurities having multiple energy levels in germanium. Pekar in Kiev had told me that he had made such calculations, and had arrived at figures that are correct to about five percent. Bonch-Bruevich is particularly interested in the trapping cross sections of various impurities in various charge states, in order to help out with the experimental program of Prof. Kalashnikov. He feels that unless Pekar has really come up with something revolutionary, there is still much to be done on this problem.

After visiting the Physics Department, I paid a shorter visit to the Cryogenics Laboratory, which is lo-

cated in a smaller outlying building well away from the main part of the Moscow University. There I spent most of my time with Miss A. Abaulina and Miss Kurova, both of whom are doctoral candidates studying the properties of semiconductors and particularly germanium at low temperatures. The apparatus used was fairly conventional, and with it Miss Abaulina was attaining temperatures down to 1°K. Their main studies were devoted to impact ionization of various impurities in germanium, and to the study of impurity band conduction in germanium at various doping levels.

One of the most intriguing features of the Moscow University physics program was the excellent laboratories devoted to the experimental laboratory courses for advanced undergraduates. Experimental arrangements covering the entire research area of semiconductors were set up in the laboratories of the Semiconductor Section, including a setup for the Hall effect, also drift mobility, lifetime by the Valdes technique, thermoelectric power, thermal conductivity, magnetic susceptibility, and others. Similar laboratory arrangements for the study of the important phenomena of superconductivity and other low-temperature phenomena were set up in the Cryogenics Laboratory.

After visiting the University, arrangements had been made to visit the Institute of Physical Problems directed by Peter Kapitza. I visited this Institute between 4:00 and 5:30 on December 3, the day before I left Russia. The Institute houses about 300 workers and is located along "Science Alley" as it might be called, because of the large number of Institutes that are located along "Bolshaya Kaluzhskaya". I entered and signed the register, as I had to do in the other laboratories of the Academy except at Kiev. However, there were no badges to wear.

Kapitza's office is a very large one, probably 35×35 feet, with a huge elegant desk and many built-in bookcases. We found Dr. Kapitza behind his desk, dressed English style, with a heavy tweed coat and slacks, smoking a pipe. Now 63, he is at the very top rung of Russian science, being not only a member of the Academy but also a member of the Presidium, the inner circle of policy-making men who control the financing and the programming of science in the Soviet Union.

The program of the Institute is mostly devoted to basic research in low temperatures. However, much collaborative work with industry is done in the application of low-temperature physics to industrial problems. For his work in developing machines for the cheap production of liquid oxygen, Dr. Kapitza received the Lenin award, one of the highest tokens of recognition in Russia. Kapitza told me that within ten years the whole Soviet steel industry will be using the new steel process based upon the use of oxygen, in which Bessemer converters are used to produce steel of open-hearth quality in less time and at much lower cost than present methods.

Kapitza is a discursive talker, who more or less sets the pace of the conversation. It is rather difficult to elicit straight answers from him, particularly to ques-

tions that are at all awkward. Rather, he is apt to respond with another series of questions.

Kapitza has engaged in a variety of extracurricular scientific projects that illustrate the agility and wide-ranging interests of his mind. One such project involved the explanation of "ball lightning" which according to Kapitza has too much energy density to be explained by ordinary mechanisms such as chemical reactions or arc discharges. His theory is that the ball represents a loop in an electromagnetic field resonating between the clouds and the earth and that energy is continuously fed into the ball from this field.

Another similar project involved the explanation for the properties of ball bearings in terms of the viscosity of the oil film and its dependence upon pressure. The main idea was that the oil film tends to spread the stress over larger areas than would be expected, and thus there is less tendency for the balls to crack or break than might be expected.

The experimental equipment of the low-temperature laboratory is excellent, and the physical arrangements in this lab were better than those of any other I visited. Excellent mechanical shops, good glass-blowing facilities, special model and instrument rooms, and even a special room devoted to fine measuring and gaging instruments were shown. The laboratory has a huge instrument room in which Dr. Kapitza took the occasion to deliver a short speech on the "cold war": "If America had not declared a cold war on us in 1946, we probably would not have all these Soviet-built instruments. We wanted to buy your instruments, but you wouldn't sell them, so we had to develop our own. Now we don't need your instruments. Wasn't that smart of you?"

About one-third of the laboratory projects are devoted to superconductivity, one-third to superfluidity, and the rest to various projects, the most important of which is the study of antiferromagnetism. We visited all the rooms where experiments were in progress, and I was much impressed by the quality of the experimental equipment. Helium supplies are excellent. There is also a good supply of helium 3, and much work is being done on this interesting substance.

As we passed one of the offices Kapitza mentioned that L. D. Landau was working there, and we talked for a while with him. Dr. Pekar of Kiev was with him, and we had a chance to renew our acquaintance. I asked Landau, who is now about 55, gray, and rather gaunt of features, of his recent activities. "Well, you know I am a man who flits about a lot from project to project, but right now I am working seriously on the theory of superconductivity." I had just the day before seen in one of the Moscow newspapers a talk by a leading Soviet scientist lauding the "new Soviet theory of superconductivity", which was solving all problems of this long-mysterious subject. I asked Landau about it and whether it had anything to do with his work or the recent theory of Bardeen and his associates. "Why, of course, this is our theory, but it is nothing but the working out of the ideas of Bardeen and his associates. Of course, when the first paper of Bardeen, Cooper,

and Schrieffer came out, we found it so confusing as to be almost incomprehensible. Later we read a paper by Cooper alone, and in it we found the real key to their ideas. We have now recast their theory into a form that seems clearer and easier to apply, and are now applying it to many properties of superconductivity. To be sure, although we found the work of Cooper to be the most significant, there is no question that all three scientists deserve great credit for a fine achievement. There is no question in my mind but that this theory will lead to a final and complete solution of the problems of superconductivity."

General Impressions of Soviet Solid-State Work

MY feeling based upon this trip is that in solid-state physics, Russia is doing excellent work, which is in a few areas ahead of our own. In most areas, and in particular that central area of theory and experiment dealing with germanium, silicon, and the technology of rectifiers, transistors, and photocells, they are still struggling to catch up with us. Although many of their projects are similar to ours in this field, there is hardly a single outstanding achievement that they have produced.

It is in the theoretical area, and such specialized areas as the thermoelectric devices area that their work stands out. The work of Frenkel, Landau, Lifshitz, Tamm, and many others is, of course, too well known to solid-state physicists to require comment. Pekar, Samoilovitch, Bonch-Bruевич, and others appear to be carrying on well this tradition of great mathematical physics.

And, of course, the low-temperature program of Kapitza's Institute, in which superfluidity was discovered and other fundamental discoveries made, will stand comparison with that of practically any other similar institute in the world.

The Russian workers seem to feel their isolation from the rest of the world, and particularly from America. So many times I was asked the question, "Why do so many of your scientific people refuse to send us reports?" Russian scientists are quite eager to travel to the West, but many are frank to admit that barriers set up by their own government as well as those set up by Western governments may prevent this.

Finally, the trip made by the author demonstrates that under present conditions it is quite possible to visit many important scientific establishments with no great formality, since in several cases appointments were made and visits carried out within a day's time with no difficulty. On the other hand, it must be remembered that personal knowledge of the visitor and his work are probably required for such a reception. In the several cases where the author attempted to visit scientific establishments somewhat outside his field and where he was not personally known, all sorts of difficulties arose, people suddenly became sick or disappeared out of town, and entire staffs suddenly went into important conferences.