(b) reaching the limiting RS accuracy (~ 0.6 mm), the accuracy of the pointing system (PS) ($5-7''$), and radio-telescope sensitivity (50–200 Jy) in all operating bands; (c) further increasing the degree of automatization; (d) finishing off the adjustment of the metrological complex in accuracy, and (e) the full-scale fitting-out of the radio telescopes with equipment complexes.

The multiband configuration of radio telescopes is based on a single large ($6\times\varnothing 2$ m) strongly misphased horn feed. Multiband observations are done with insignificant loss of sensitivity and minimum alterations in the design of the radio telescopes. The radio-telescope frequency range can be broadened in order to incorporate millimeter waves and ensure a planned increase in RS and PS accuracy under certain restrictions on weather conditions. Experimental observations at $\lambda = 1.35$ cm with a beam width smaller than $1'$ confirmed high PS stability and clarified the top-priority measures needed to increase sensitivity. The multiband feed with a broadened frequency band was developed in cooperation with the Antenna Department of MPEI by numerically solving the exact electrodynamic problem with allowance made for the manufacturers' tolerances and the frequency bands.

The overall accuracy of measurements and adjustments achieved in the staged radio-holographic alignment of RS at Bear Lakes (in cooperation with the Radiophysics Research Institute — NIRFI, Nizhniĭ Novgorod) was 0.2–0.25 mm. Earlier (1980–1986) a laser long-range profilometer was built for performing alignments of RS at all inclinations of the reflector. The first laser station that emitted nanosecond pulses and monitored the coordinates of an aircraft with an onboard radio-frequency reference was devised and used for measurements involving large antennas in the period from 1974 to 1984. To increase the degree of homology of RS, effects associated with gravity, thermal, and wind strains in the system were studied and compensated. From 1980–1985, the effectiveness of photogrammetry and radio range-finder checking of strains in the reflector was investigated.

The accuracy of PS angular adjustments in the hemisphere was brought up to $2''$. The residual angular errors and the problem of their compensation are studied. The automatization of tracking and multiple rapid transfers from object to object in the around-the-clock operation was completed, while work on automatizing the test, metrological and auxiliary modes is still going on.

A precision automated metrological complex was built and is being gradually modernized. The complex is used in conjunction with radiometric, radio holographic, radio-direction-finding, and geodesic systems and the corresponding technologies.

Radio telescopes operate regularly and effectively in international VLBR networks, thus increasing the overall sensitivity of such networks and broadening the spatial frequency range. Researchers have extracted new data from observations made with radio telescopes. The Institute of Space Research (IKI) of the Russian Academy of Sciences has obtained a radio image of the jet of the radio galaxy 3C274 and that of a maser in the gas-dust complex W51. The Astrocomplex project of PRAO ASC FIAN is aimed at investigating the fine structure of fluctuations of the time and direction of arrival of r.f. pulses from millisecond pulsars in the timing and VLBR modes. ASC FIAN, in collaboration with KA HALCA (Japan), obtained a radio image of the quasar 3C147 with enhanced resolution in the ground-space interferometer mode. Radio telescopes form a unique equipment base for collective usage due to the combination of high sensitivity, accuracy, universality, reliability, and cost effectiveness.

4. Conclusion

The above findings represent the core of the solution found by SRB MPEI (with the participation of several other research and industrial organizations) for the comprehensive scientific and technological problem of building and extensively using large optimized antennas and radio telescopes with their supplying equipment for space and radio-astronomy systems.

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Molecular beam epitaxy: equipment, devices, technology

O P Pchelyakov

1. Introduction

The synthesis of semiconducting thin-film compositions from molecular beams in ultrahigh vacuum became known as a new method in semiconductor materials science after the first successful experiments by Arthur and LePore [1] and Cho [2] at the end of the 1960s. This method, known as molecular beam epitaxy (MBE), gained momentum largely due to the development of unique micro-, nano-, and optoelectronic devices around structures with superlattices, quantum wells, and quantum dots, whose principle of operation is based on the wave nature of the electron (in contrast to the more common microelectronics devices). Among such devices are, primarily, semiconductor lasers and sensitive photodetectors with quantum wells, superlattices, and quantum dots in the active region; transistors with high electron mobility in the conduction channel; nanotransistors; tunnel-resonance diodes, and single-electron devices, etc. At present additional impetus to R&D in MBE is provided by the ideas and perspectives favored in building an elemental base for quantum computers. At the same time (and with the same intensity), scientific instrument making is being developed for this area of vacuum technology and analytical equipment.

Industrial realization and development of the molecular beam epitaxy method have convincingly shown that the method is indispensable in manufacturing multilayer epitaxial structures with atomically smooth boundaries and layer thicknesses, composition, and alloying profiles that are monitored with high precision. The use of highly sensitive electron-probe and optical instruments for monitoring the parameters of the new structures and controlling the process of their synthesis ensures the high reproducibility of these parameters.

The story of how this important avenue of research in scientific instrument making was founded and developed at the Semiconductor Physics Institute (SPI) of the Siberian Branch of the Russian (then Soviet) Academy of Sciences (RAS) and in the USSR as a whole was closely related to the names of two outstanding scientists: the first director of SPI Academician A V Rzhanov, and the founding father of the leading scientific school in Russia in the physics and technology of molecular beam epitaxy, Prof. S I Stenin. The first ultrahigh-vacuum MBE facility at SPI became operational in 1979. At that time the work on building an experimental base for MBE had been lagging behind similar work done abroad in developing devices and equipment in this field of research. The aim was to overcome the dependence on foreign equipment in this area of advanced technology.

2. MBE equipment

According to the scientific literature, at the beginning of the 1980s the Soviet Union had several MBE facilities built by Riber (France) that were located, primarily, in scientific research institutions belonging to various ministries, and a small number of ultrahigh-vacuum sputtering facilities imported or made in the USSR that were not directly intended for fabricating films by the MBE method. The most interesting work in building facilities for MBE of silicon and germanium was done in Great Britain, France, the USA, and Japan in such companies as VG-Semicon, Riber, Varian, Ulvac Corporation, Anelva and some others. The leaders of Soviet ultrahigh-vacuum engineering industry were the Scientific Research and Technology Institute (Ryazan'), the S A Vekshinskiĭ Scientific Research Institute of Vacuum Technology (Moscow), the Analytical Instrument Making Special Design Office (St. Petersburg), the Burevestnik Research and Production Association (St. Petersburg), and the RAS Scientific Instrument Making Experimental Plant (Chernogolovka, Moscow region). These institutions contributed substantially to the development of Soviet equipment for MBE of $A^{III}B^{V}$ compounds [3, 4], but did not produce equipment for the epitaxy of elementary semiconductors and $A^{II}B^{VI}$ compounds. In Russia (then USSR) the development of support equipment and the scientific basis of the technology for all these types of semiconductors was carried out only at SPI SB RAS. It started ten years later than the first publications on the subject appeared in the world scientific literature, but the high momentum of research made it possible to reach world standards by 1992 in the quality of producing the necessary facilities and multichamber MBE complexes. At SPI, the principles of building such complexes have been established, the optimum set of analytical tools for monitoring the growth process has been determined, and the design and technological characteristics of such MBE equipment as Angara and Katun' have been described [5]. The complete configuration of such equipment included a module for preparing and analyzing substrates, a module for the epitaxy of semiconductor films, and a module for depositing metallic and insulating layers. The equipment was attached to a computer system for controlling the technological process.

The following analytical devices built into the MBE equipment modules have been developed (and are still manufactured) at SPI:

(1) Recording high-energy electron diffractometers (HEEDs) for monitoring the structure of substrates and films and for determining the growth rates and thicknesses of the films and the concentration ratios of the main components in solid solutions;

(2) Built-in laser ellipsometers for measuring thicknesses and optical properties. Such a device, in combination with specially developed techniques and computer software, can also be used for measuring the film composition, surface microroughness, and even the temperature of the surface layers of films [6, 7]. Ellipsometry has markedly broadened the possibilities of nondestructive *in situ* testing of the film properties, especially in cases where the use of HEEDs is impossible (high pressure in the molecular beam or low radiation resistance of the growing films);

(3) Specially designed polarization pyrometers for noncontact measurement of the sample's surface temperature.

Since 1987, Angara and Katun' type MBE devices have been manufactured in small batches at the experimental facilities of SPI and at the Pilot-Production Plant of the Siberian Branch of the RAS. From 1987 to 1992, 35 sets of equipment were manufactured, which included 79 growth and analytical ultrahigh-vacuum modules, more than 100 electron diffractometers, and 25 laser ellipsometers.

During recent years, continuing to perfect the MBE techniques and technology, SPI in cooperation with the S P Korolev Energiya Rocket and Space Corporation (Korolev, Moscow region) and the 'Science Center' Research Institute (Zelenograd, Moscow region) have been developing the experimental equipment and devices needed for MBE in space near orbital laboratories behind a molecular screen [8]. The E O Paton Electric Welding Institute (Kiev, Ukraine) is also beginning to participate. The goal of this joint project is to overcome the crucial restrictions imposed on the MBE process by conditions on the Earth when extremely high-quality structures are manufactured in vacuum devices. The limiting factors here are the purity and depth of the vacuum, the performance of the pumps, the presence of walls in the vacuum chamber that accumulate and give off the molecular beam components, and an atmosphere of residual gases. These deficiencies can be eliminated by sending the technological set-up into space to the 'wake region' of the molecular screen [8 – 10]. In accordance with the Program for Realization of Scientific and Applied Research in the Russian segment of the International Space Station, the first experiments are planned for the year 2003. At present, SPI laboratories are carrying out ground tests of the MBE processes, making an operational station that imitates the conditions in space, and testing the components of supporting technological equipment.

3. Instrumental realization of epitaxial structures

To illustrate the possibilities of the new apparatus for MBE, a list of some modern devices manufactured on the base of epitaxial structures grown at SPI using Katun' type facilities is given below. The characteristics of these devices were described in the publications cited:

(a) Gunn diodes of the millimeter range (28 GHz) [11];

(b) GaAs-based integrated circuits [11];

(c) Silicon field transistors with Ge quantum dots embedded in proximity with the *p*-type conductive channel [12];

(d) Light-sensitive matrix modules of the IR range (3 – 5 μm) based on a GeSi/Si heterojunction [13];

(e) IR lasers with a vertical cavity and radiation powers up to 20 W per pulse with a wavelength of 0.95 μm [14], and

(f) Matrix IR (5 μm) photodetectors on CdHgTe films [15]

4. Conclusion

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Low-temperature scanning tunneling microscopy

V S Édel'man

Soon after Gerd Binnig and Heinrich Rohrer invented the scanning tunneling microscope (STM) in 1982, Khaĭkin [1] developed the first STM in the USSR, which signalled the beginning of research in scanning tunneling microscopy and spectroscopy in our country. In his laboratory, Khaĭkin and collaborators [2] developed a number of microscopes used for various purposes: a STM with a wide field of view compatible with a scanning electron microscope [3]; a simple high-vacuum STM [4]; a high-vacuum STM with its sharp tip positioned within a range of several millimeters along the three coordinate axes [5], and a low-temperature STM submerged into a transport Dewar vessel containing liquid helium [6].

The logical development of this work was the production of a cryogenic high-vacuum installation used in scanning tunneling microscopy [7, 8]. The need for low-temperature scanning tunneling microscopy stems primarily from the fact that many phenomena and processes, such as superconductivity, the transition to a state with charge density waves, magnetic ordering, and sorption of gases, are realized only at very low temperatures. The cooling of the sample makes it possible to eliminate the thermal fluctuations of the atomic terrace boundaries, namely, fluctuations that sometimes already manifest themselves at room temperature [9]. Even for research that can be done at room temperature, the cooling of STM to helium temperatures proves to be effective since in this case the thermal drift of the device is eliminated, i.e. for all practical purposes it is zero.

Usually low-temperature high-vacuum devices employ costly industrial ultrahigh-vacuum systems augmented by cryogenic insertions (see Volodin's review [10]). The present author used a different approach and placed the STM in a cavity whose walls were cooled to liquid-helium temperatures, which automatically solves the problem of achieving ultrahigh vacuum. This method makes it possible not only to maintain the necessary conditions for conducting the experiments but also to eliminate the problem of poor thermal contact between the sample and the liquid helium in the vessel by feeding gaseous helium into the chamber. According to observations, the presence of helium has no effect on the results of experiments involving scanning tunneling microscopy and spectroscopy.

The apparatus uses an STM [5] with a sample holder that allows *in situ* heating up to 500 – 600 K with a heater power amounting to approximately 1 W [11]. To remove heat from the microscope in the event of prolonged annealing, we used a copper heat conductor and a mechanical heat switch connecting the microscope with the liquid-nitrogen bath. In this way the heat load on the vessel with liquid helium could be reduced to the acceptable level of 0.1 – 0.2 W.

The apparatus was used to study the structure of a surface of Bi formed by *in situ* cleavage (Fig. 1). It was found that, for cleavage of the crystal at low temperatures, atomically smooth terraces with straight boundaries oriented strictly along atomic rows are usually formed [12, 13]. This is an indication that there is a certain 'inertia' in the motion of a terrace boundary as the crystal is destroyed.

It was also found that the atomically smooth portions do not possess strict translation symmetry, since on the perfect atomic pattern some relief is superimposed with a random structure and characteristic dimensions in the plane amounting to several interatomic distances. Accordingly, the current – voltage characteristics vary from point to point over the surface. This suggests that the density of the electron states is nonuniform. Probably, these features are related to the presence of defects beneath the surface, which are generated in the process of crystal cleavage [14]. The nonhomogeneity of the surface is retained when the sample is heated to virtually the melting point, which makes it possible to estimate the activation energy of the defects at 1.5 – 2 eV. Such values are typical of vacancies.

The most interesting and unexpected phenomenon is the emergence of twin microlayers of quantized width (see Fig. 1). Their width is determined by the fact that the atomic layers in the microlayer that are inclined (at a small angle of 2.34°) to the layers in the rest of the crystal, which are oriented at right angles to the trigonal axis, are 'matched' at the boundaries. Only the uppermost layer 'matched' with the matrix on one side forms a step of height 0.2 nm on the other side [15, 16]. According to the results of measurements of current – voltage characteristics, in a region whose width is one to two atomic rows near the step, a one-dimensional conductor forms with a concentration of conduction electrons much higher than on the rest of the surface. A similar phenomenon is also observed near the boundaries of ordinary terraces.

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