PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Low-Dimensional Modulated Structures [and Discussion]

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Low-dimensional modulated structures

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The second microchip age that is developing includes optoelectronic devices, in contrast to electronic devices, such as the transistor, the basis of the first microchip revolution. For optoelectronic devices the electronic carriers must be confined in at least one dimension, giving thin layers, which are then stacked or alternated for greater reliability and efficiency. The material of choice for electronic devices has been the elemental semiconductor silicon, whereas efficient optoelectronic conversion requires compound semiconductors such as GaAs. Confinement is achieved by alternating large energy gaps (AlAs) with small gaps (GaAs). For communications purposes the operating optical wavelength must be matched to the pass band of kilometric optical fibres, which in turn has led to the design and production of quaternary semiconductor alloy sandwiches. Although the economics of compound semiconductor materials is much less favourable than that of Si, junction lasers made from these materials with less stringent specifications are already appearing in popular consumer items such as compact-disc players. New research indicates that Si–Ge alloys fabricated on Si may replace the AlAs–GaAs layer structures in some applications, with large savings for high-quality optoelectronic devices.

1. Introduction

The general principles governing semiconductor electronic devices are easily understood by analogy with electrical currents in vacuum, and indeed it was these analogies that inspired the original invention of the transistor by J. Bardeen, W. Brattain and W. Shockley in the late 1940s. They imagined that electrons carrying electrical currents in solids might be controlled by applied electric fields, analogous to electrons carrying current in vacuum tubes. The suitable material for realizing this analogy is a semiconductor such as Ge or Si, where a small number of electrons carrying current is available at room temperature. Thus described, the idea seems quite simple. Its actual realization, first scientifically and then technologically, depended centrally upon preparation and production of semiconductor materials whose properties on an atomic scale fulfilled the requirements of the idealized simple model.

Since the invention of the transistor, semiconductor electronic technology has advanced with breathtaking rapidity and fresh advances are still being made. Although these advances in electronic technology are still being made, and will surely continue to be made in the 1990s, I will concentrate here on the emerging optoelectronic devices that can also be made from semiconductors. These devices usually have layered structures, and the chemical composition is modulated from layer to layer. Typical layer thicknesses are about 10 nm or less.

2. Optoelectronic devices

The feature that distinguishes a semiconductor optoelectronic device from a merely electronic device is efficient interconversion of optical and electrical energy. Sometimes coherent light is generated by electrical currents, and the most dramatic technological applications involve coherent light. However, efficient conversion in itself brings many technologically valuable rewards. For such efficient conversion to take place, the material properties of the semiconductor must be carefully controlled.

To understand the conditions that must be fulfilled for efficient interconversion of optical and electrical energy in semiconductors, let us begin by reviewing the electronic energy levels of crystals. On a coarse scale these resemble discrete atomic-energy levels that have been broadened into bands by the overlapping of periodically repeated atomic potentials. In semiconductors these energy bands are divided into valence-band bonding states and conduction band antibonding states, separated by a forbidden energy range ΔE_{cv}, which is typically about 1 eV (in energy) or 1 μm (in wavelength of light).

Suppose we now have a pure and perfect semiconductor crystal at $T = 0$. Then each valence bond contains two electrons and the valence band states are likewise each occupied by two electrons, in accordance with the Pauli–Fermi exclusion principle, with the two electrons having spin up and spin down. With increasing temperature some electrons are thermally excited from the valence band to the conduction band. The states left vacant by the excited electrons are called holes and these missing electrons behave as positive charges that compensate the negative charge of the excited electrons.

Ordinary transistor currents are carried by these electrons and holes. By substituting impurities containing one more (or less) valence electrons than the atoms of the host lattice, e.g. substituting P (or B) for Si, we can upset the balance of electrons and holes in specific regions of the material. Such doping is used to make a variety of electronic devices.

In optoelectronic devices attention is focused on producing electrons and holes, for example, by optical or electrical excitation, and then causing them to recombine. Electron and hole recombination is undesirable in electronic devices, because it depletes electronic currents. However, in optoelectronic devices the goal is to induce efficient electron–hole recombination at a fixed energy difference (photon energy or light wavelength). In effect, electron–hole pairs are generated over a wide energy range, and then are made to recombine to emit light over a very narrow range. This spectral compressive effect is the key feature of optoelectronic devices.

3. Diode lasers

Just as the transistor is the prototypical microelectronic device, so the semiconductor diode laser is the representative optoelectronic device. These devices were described in a popular article (Panish & Hiyashi 1971), which I follow closely. The basic element in the semiconductor laser is a p–n junction, which is also the basic element in a transistor. Its energy-level diagram is shown in figure 1. The energy levels in the p and n regions are offset because in the p(n) region the material is doped with impurities that introduce additional electronic states near the top of the valence band (bottom of the conduction band). This offset can be altered by applying a voltage drop across the sample, with a large fraction (near one half) of the drop occurring across the junction, also shown in figure 1.

The critical material parameters of the diode junction laser are the width and the perfection of the junction region. By the perfection of the region, I mean both its abruptness and the absence of crystalline defects (such as missing atoms) in the active region where the electrons and holes are intended to recombine.

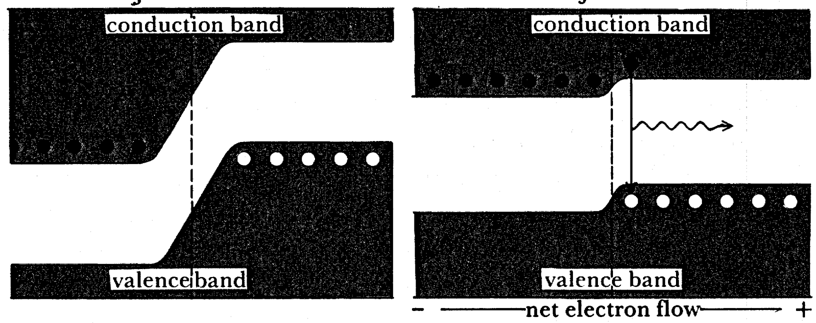

FIGURE 1. The energy levels of an unbiased p–n junction with a few excited electrons (holes) shown as filled (empty) circles are sketched on the left. A junction under forward bias is illustrated on the right (Panish & Hiyashi 1971).

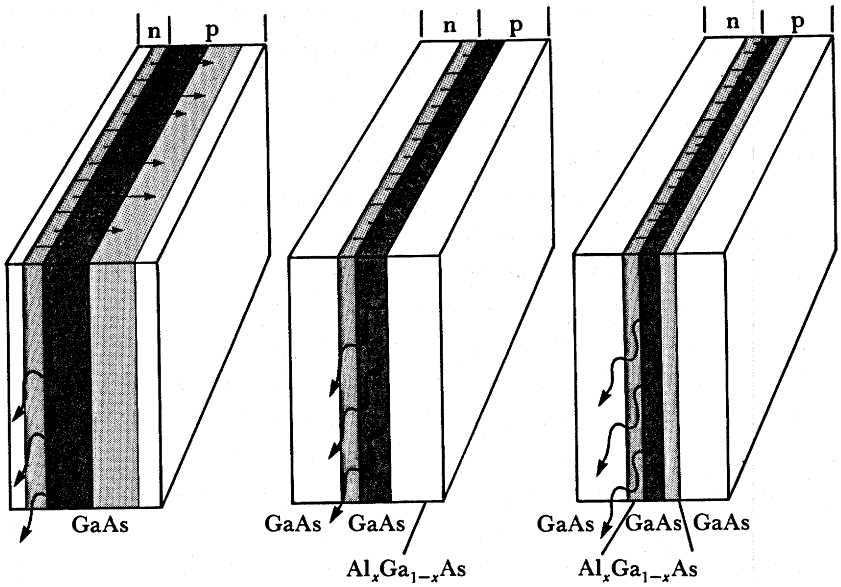

FIGURE 2. Three types of junction lasers are shown here: a p–n junction on GaAs on the left, a single heterostructure in the centre, and a double heterostructure on the right. Forward-biased electron currents in the samples are indicated by arrows, and light is emitted from the active region towards the reader, also as indicated by arrows (Panish & Hiyashi 1971).

4. MATERIAL CHARACTERISTICS

Another critical parameter is the semiconductor material itself. Excited electrons in the conduction band thermalize down to energies of the order kT ($=\frac{1}{40}$ eV at room temperature) in a band whose full width is of the order 3 eV, and similarly holes float 'up' to the edge of the valence band. In Si, optical transitions between these two band edges occur very weakly, which is a favourable feature of Si microelectronic devices, because it means that electrical currents suffer less attrition due to electron–hole recombination. However, for optoelectronic devices large transition rates for electron–hole recombination are necessary. The material with large transition rates which can be most easily grown as nearly perfect crystals is GaAs, a

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compound semiconductor which has a crystal structure similar to Si and which also has on the average four valence electrons per atom.

As we shall see presently, nearly perfect compound crystals (such as GaAs) are more difficult to grow than elemental crystals (such as Si and Ge). However, once one chooses GaAs for its high optical efficiency, one can exploit the additional flexibility offered by compounds to achieve further confinement of the carriers. This is done by alternating layers of GaAs with layers of $Al_xGa_{1-x}As$, as shown in figure 2. The latter alloys have larger energy gaps between the valence and conduction bands. Broadly speaking, the electrons and holes seek the region of smallest energy gap (GaAs), and this additional confinement enhances the rate of electron–hole recombination. Large values of this rate, compared to resistive joule heating, are needed to produce laser action without damaging the sample, for example by local melting.

5. Carrier confinement

The recombination of electrons and holes driven by a voltage drop across the junction is resisted by diffusion. The average diffusion length of carriers (before, for example, being trapped at defects) is several micrometres. Early diode lasers, made with GaAs p–n junctions, used junction widths of the order of a fraction of a micrometre. Thus the junction itself provides some carrier confinement, and in this way junction laser operation was observed nearly simultaneously in 1962 by three independent groups. The early junction lasers, however never could be operated continuously at room temperature without damage from joule heating. In the intervening decades increased carrier confinement and very high levels of material perfection have made junction lasers a technological success.

In a nearly pure material, electrons and holes recombine in laser action from their lowest energy state, where the electron and hole are bound to each other by their Coulomb interaction (similar to ground state of a hydrogen atom). The dimensions of this state are of the order 5 nm. Confinement of electrons and holes in GaAs regions by $Al_xGa_{1-x}As$ walls increases recombination rates until the walls are about 5 nm apart. This is a considerable improvement from dimensions of order 10^3 nm as used in 1962. The evolution of materials technology over the last several decades has been towards development of techniques that permit fabrication of these ultra-thin layers.

6. Sample growth

In early work, samples were grown from the melt by carefully controlling temperature gradients to produce material with low defect concentrations (Panish & Hiyashi 1971). Layer thicknesses in samples grown by this method (called liquid-phase epitaxy) were typically 100 nm. An unexpected, but happily fortuitous, feature of these multilayer structures is that the laser light is confined to the electrically active GaAs regions by internal reflection from the $As_xGa_{1-x}As$ walls, which facilitates laser action at much lower threshold currents, lower, in fact, by a factor of about 25 from the best results obtainable without alloy confinement. Thus it became possible to produce multilayer alloy confinement lasers that operated continuously at room temperature for up to one year.

This laboratory success, however, proved technologically insufficient. In practice, control of temperature gradients in the melt is difficult, and most of the junction lasers produced by liquid-phase epitaxy had short operating lifetimes. After a decade of research it became evident

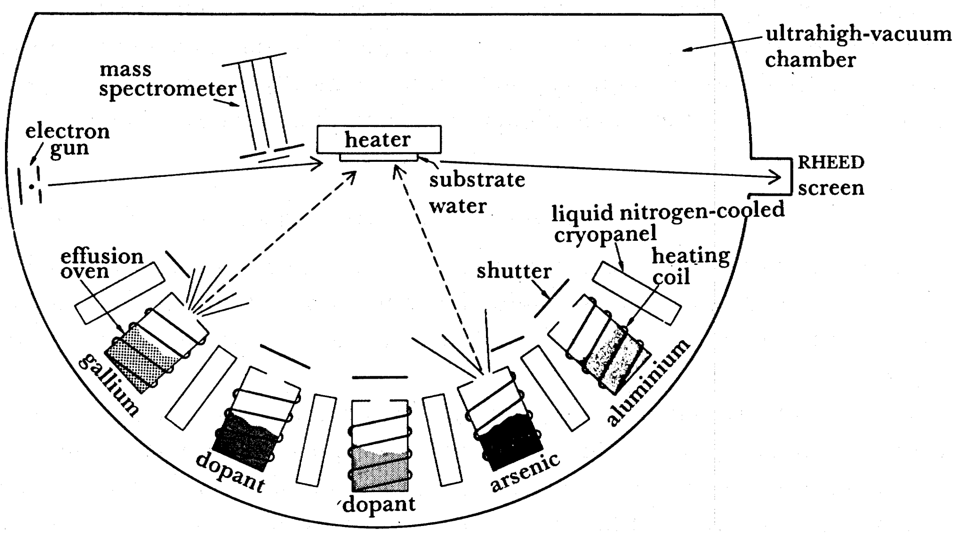

FIGURE 3. The components of an ultra-high vacuum (10^{-11} Torr background pressure) apparatus used to grow samples by molecular-beam epitaxy (Panish 1980).

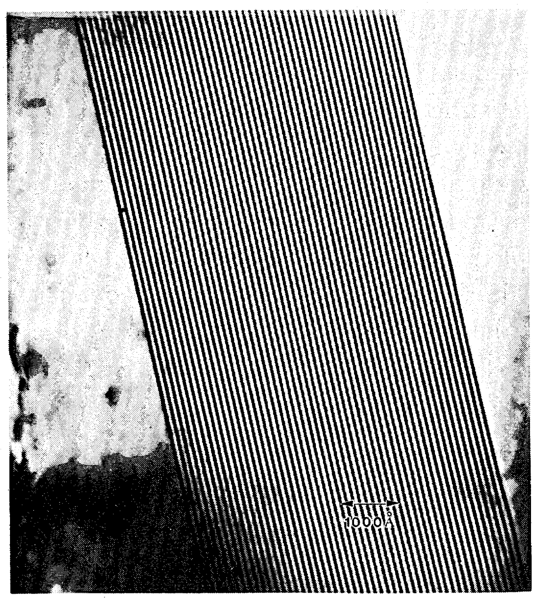

FIGURE 4. Transmission-electron micrograph of a 50 multilayer structure consisting of alternating 125 Å layers of $Ga_{1.5}In_{0.5}As$ and InP grown by MBE. (Figure courtesy of M. B. Panish.)

that technological success required material growth on almost an atom-by-atom basis and this is just what has been achieved by MBE (molecular beam epitaxy) (Panish 1980). A sketch of a molecular beam system is shown in figure 3. With these systems nearly perfect samples may be grown at rates at low as one atomic layer s^{-1}, which indeed is almost an atom-by-atom basis. Distinguishable layers one or two atomic layers thick (0.3–0.6 nm) have been stacked to form films of thickness 10^3 nm to demonstrate the capabilities of MBE. Typical thicknesses of the active layers in optoelectronic devices are, however, much larger, of order of tens of nanometres, as shown in figure 4.

One of the characteristics of thin layers is a large surface: volume ratio. This means that layer interfaces must achieve perfection comparable to bulk material, and it is this requirement that makes molecular-beam epitaxy (MBE) technologically essential compared to liquid-phase epitaxy (LPE). With MBE much higher yields and more reproducible device characteristics are achieved.

7. Technology of modulated structures

Recent technological progress in the use of optoelectronic devices is substantial, and as is often the case much of the information is proprietary. I mention here some steps known to me, but the following list is by no means complete. It is presented in order to illustrate some recent aspects.

For communication purposes, optical fibres are replacing coaxial cables and microwave transmission as well as satellite relays wherever possible. Optoelectronic devices are used as signal sources and detectors in fibre-optics communications systems. Coaxial transatlantic systems were first used in 1955 and 1956 with 50 voice channels and repeater spacings of 70 km. By 1976 and 1983 these had improved to 4200 voice channels with a repeater spacing of 9.4 km. The optical-fibre cable expected to become operational in 1988 has a capacity of 40000 voice channels and a repeater spacing of 50 km.

Once the material forming the laser diode has been made, the engineering problems which must be surmounted for technological applications may turn out to seem almost too easy in retrospect. A good example is the so-called multimode problem. For several years engineers struggled with this problem, which arises because the laser cavity can operate in several different fundamental normal modes. For frequency modulation single mode operation is necessary. One way to suppress unwanted modes is through elaborate cavity geometries. The recently discovered C^3 (cleaved coupled cavity) laser uses a much simpler method (Tsang 1984). A laser is cleaved into two parts, with slightly different resonant frequencies. One of these is operated above threshold and lases; the other is placed with the cleaved faces in close proximity and is operated below threshold. The current of the second laser is varied to tune one of its normal modes to match that of the first laser, whereupon both parts lase, but only in the matched mode. Apart from its great technological value, the C^3 laser can be regarded as a paradigm of engineering simplicity that may be easily obtained with optoelectronic devices in contrast to the complexities of traditional microwave systems.

8. New materials

The central reason why GaAs and $Al_x Ga_{1-x} As$ are widely used as optoelectronic materials is chiefly convenience, especially for larger-scale geometries where the high purity of GaAs and the close match of lattice constants of GaAs and AlAs are favourable factors. However, as device miniaturization has become easier through MBE, other material combinations have become technologically attractive. In fibre-optic systems the minimum attenuation and dispersion wave length of the glass fibre corresponds closely but not exactly to the laser emission wavelength of GaAs. With attenuation and dispersion lengths of the order 50 km, it is obviously desirable to match the laser to the fibre. This can be done by using $In_x Ga_{1-x} As_y P_{1-y}$ quaternary alloys as the active region with InP walls. Recent MBE quaternary-alloy laser devices achieve performance levels comparable to those of AlGaAs GaAs devices.

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Another avenue of active research has strong overtones of *déjà vu*. Although neither Ge nor Si is optically efficient, in limited contexts (for optoelectronic devices internal to a Si chip, for example), the ability to grow epitaxial $Ge_x Si_{1-x}$ alloys on Si chips is technologically promising (Bean 1985). The technological capabilities of the Si chip industry are formidable, but the physical principles operating against efficient optoelectronic devices in these materials are fundamental. It will be interesting to see which prevails. The high level of research activity in this field at present suggests that much 'smart money' is bet on technology.

9. Conclusions

The semiconductor material technology begun by Bardeen, Brattain and Shockley in the late 1940s shows no sign of flagging. Together with atomic fission it is clearly the greatest technological advance in inorganic science of the twentieth century.

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Discussion

J. H. Westbrook (*Knowledge Systems, Scotia, New York, U.S.A.*). What materials developments led to the improved optical properties (bandwidth and attenuation) in silica optical fibre?

J. C. Phillips. The central improvement was the increase in attenuation lengths, which are now of the order of tens of kilometres. This was achieved by purifying the silica core by removal of (mostly transition and alkali) metal impurities and H_2O, with impurity levels less than one part in 10^7.

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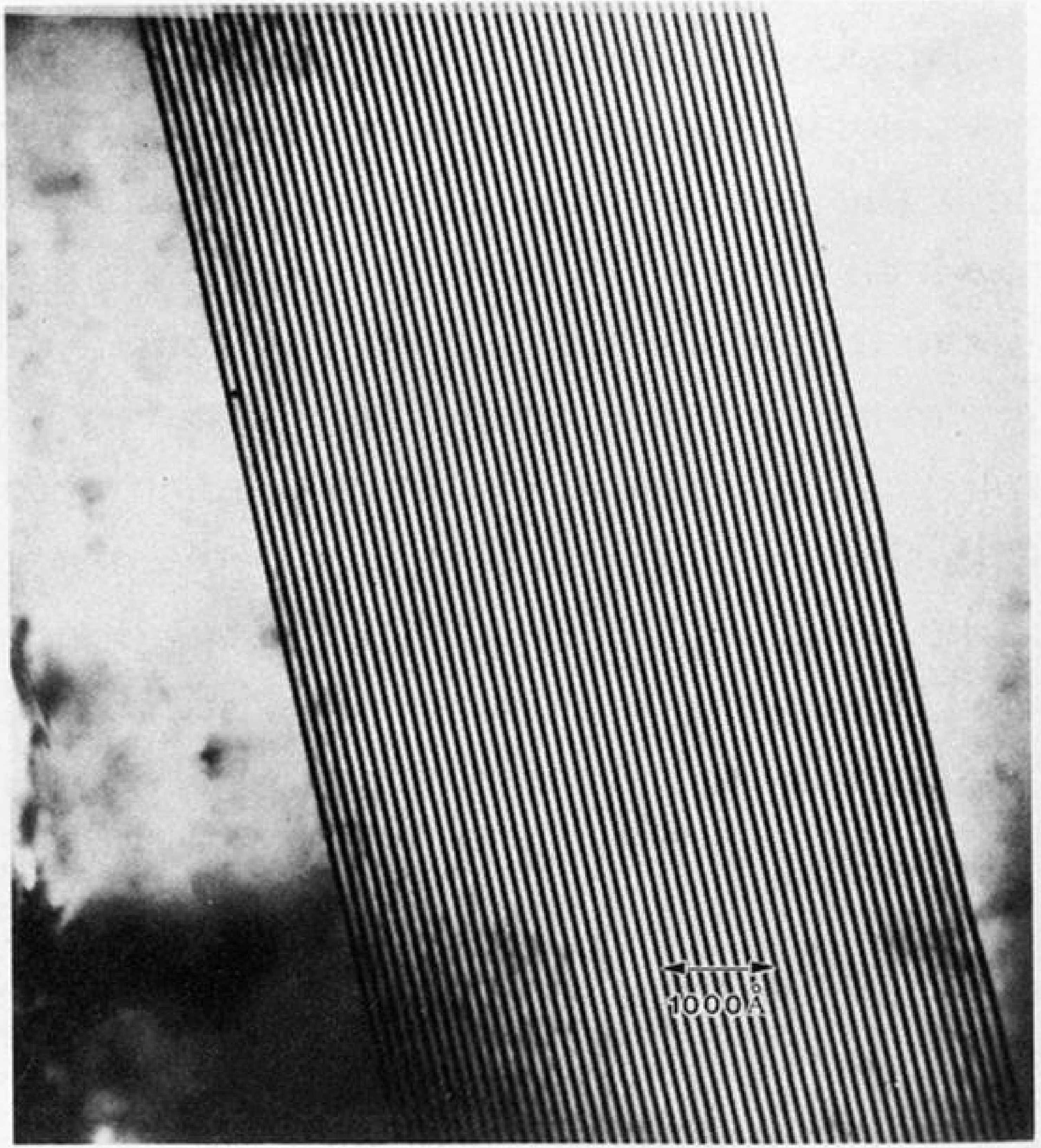

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