

Isotope engineering

V G Plekhanov

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Abstract. Major applications of the novel and extremely promising technology of isotope engineering are reviewed which, along with basic research, also include — by no means exhaustively — optical fibers, optoelectronics, tunable solid-state lasers, neutron transmutation doping, and information storage.

1. Introduction

Most chemical elements have more than one stable isotope (e.g. see Ref. [1]). According to modern ideas of nuclear physics, isotopes (the concept of an isotope was introduced nearly a century ago by F Soddy [2]) are the atomic nuclei of the same chemical element with different numbers of neutrons. Thus, the isotopes of a chemical element differ only in the mass of the nucleus and, hence, in the frequency of the ultimate optical and zero-point oscillations, which in turn leads to marked transformations of the energy spectrum of electronic excitations [3–5]. Among these transformations, of primary importance is the well-known variation of the interband transition energy E_g on isotopic substitution. While in Ge the value of E_g changes by roughly 1 meV on isotopic substitution, in diamond and in $\text{LiH}_x\text{D}_{1-x}$ crystals this change amounts to 13 and 104 meV, respectively. In the latter case, the values are rather large, which means they can easily be measured using modern techniques of experimental physics. It must also be noted that in the case of $\text{LiH}_x\text{D}_{1-x}$ crystals subjected to isotopic substitution, the exciton binding energy varies nonlinearly by 20% (from $E_B = 40$ meV for pure LiH to 50 meV for pure LiD [5]). Quantitative studies of the concentration dependence of E_B

have made it possible to extract entirely new information about the exciton–phonon coupling constant in the case of the Fröhlich mechanism of scattering of free excitons by LO phonons, the exciton translational mass, the mass of current carriers, etc. (for more details see Ref. [5]). The isotope effects in lattice dynamics are thoroughly discussed in Ref. [6].

When speaking of lattice dynamics, one should first be concerned with the effect of isotopic substitution on the elastic, thermal, and vibrational properties of the crystal lattice. While the variation of the lattice constant $\Delta a/a$ is roughly $10^{-3}–10^{-4}$, the variation of the elastic constants, δc_{ik} , amounts to several percent. Isotopic substitution also gives rise to highly distinctive and general effects in the phonon spectrum, especially in the LO-phonon spectral region. The shift of LO lines in diamond does not exceed 50 cm^{-1} , while in $\text{LiH}_x\text{D}_{1-x}$ crystals it exceeds 200 cm^{-1} . Such a profound effect in the case of $\text{LiH}_x\text{D}_{1-x}$ crystals is due primarily to the strong scattering potential which is caused by the substantial change in mass in the process of isotopic substitution.

The coherent potential model provides a quantitative description of the small shifts of the lines and the line broadening in the spectrum of light scattered in semiconducting crystals (Ge and C) (see also Ref. [3]). The presence of local vibrations in the spectrum of light scattered in $\text{LiH}_x\text{D}_{1-x}$ crystals, as well as the two-mode nature of LO phonons at high isotope concentrations, make it impossible to use the linear approximation of the coherent potential method in describing the lattice dynamics of these crystals. We mention in passing that in the event of isotopic substitution the peak thermal conductivity in enriched ^{70}Ge (99.99%) is $k_m = 10.5\text{ kW m}^{-1}\text{ K}^{-1}$, or ten times greater than in natural germanium (the same is true of C and Si). Despite these large effects being present in the various characteristics of a solid on isotopic substitution, so far very few attempts have been made to utilize structures with an ordered (or disordered) distribution of the different isotopes of one chemical element in practical applications. Probably the only important exception here is the employment of isotope

V G Plekhanov Institute for Computer Engineering and Science,
ul. Erika 7a, 10416 Tallinn, Estonia
Tel. (10-372) 6 603 150
E-mail: vgplekhanov@hotmail.com

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engineering in transmutation transformations which are considered in greater detail in Section 5.

The present paper is a brief review of the potential and real applications of isotope engineering to insulators and semiconductors, which is by no means untimely problem from the standpoint of the practical aspect of fundamental research. The second (no less important) reason for this review is to focus the attention of researchers, including applied physicists, on a new and promising area of science.

2. Isotopic confinement of light and phonons

The first (and most important) application of the isotope technology is optoelectronics with isotope-varied elements and, in particular, optical fiber. As is known, for a typical solid of different isotope composition the lattice constant varies within the following limits [6, 7]:

$$\frac{\Delta a}{a} \sim 10^{-3} - 10^{-4}. \quad (1)$$

For instance, modern precise experimental data yield a value of $\Delta a/a = 1.5 \times 10^{-4}$ for diamond crystals of different isotopic composition, while for $\text{LiH}_x\text{D}_{1-x}$ crystals it is 0.0037 for the limiting values of x (for more details see Ref. [6]).

Let us assume that the optical fiber is manufactured from a single chemical element of different isotopic composition: the core region is made of one isotope and the cladding, of another isotope of the same chemical element. The boundary between the core and the cladding forms the isotope interface. The difference in the values of the refractive index on the two sides of the isotope interface gives rise to total internal reflection and, hence, may ensure an alternative path which leads to light confinement. For a quantitative estimate we examine the interface between isotopically different compositions of SiO_2 , where the materials of the core and cladding have the same chemical composition and structure but different isotopic composition, for example, $^{28}\text{Si}^{16}\text{O}_2$ and $^{30}\text{Si}^{18}\text{O}_2$, respectively (Fig. 1). As a first approximation we assume that the refractive index is proportional to the number of scatterers in a unit volume. Using the Clausius–Mossotti equation (e.g. see Ref. [8]) for the refractive index, we arrive at the following relationship (true for $\Delta n \ll n$):

$$\frac{\Delta n}{n} \approx 3c \frac{\Delta a}{a}, \quad (2)$$

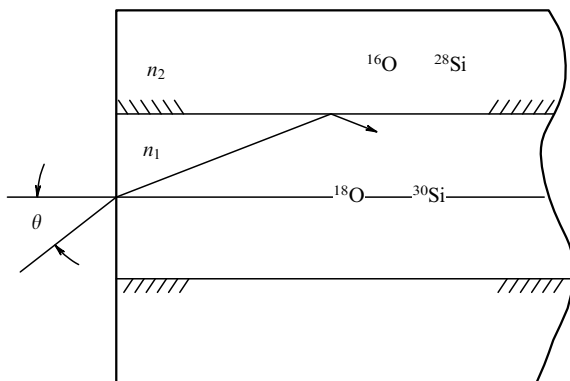


Figure 1. Isotopic fiber in which the core and cladding are manufactured from pure SiO_2 of different isotopic composition [7].

where c is a dimensionless adjustable parameter of order unity (see also Ref. [7]). Substituting (1) into (2), we obtain

$$\frac{\Delta n}{n} \sim 3 \times (10^{-3} - 10^{-4}). \quad (3)$$

Applying the Snell law of light refraction, we arrive at the following expression for the angle of refraction Φ when monochromatic light travels through a refractive boundary:

$$\Phi = \arcsin \left[\frac{n_1}{n_2} (\sin \alpha) \right], \quad (4)$$

where α is the angle of incidence. (For a grazing ray $\alpha \approx 90^\circ$. This condition ensures the confinement of light to the fiber.) Combining Eqns (3) and (4) yields the following estimate for the angle of refraction:

$$\Phi \sim 0.2 - 4.5^\circ. \quad (5)$$

Thus, the use of an isotopic fiber in which the core and cladding are manufactured from different isotopes of the same chemical element is sure to guarantee an angle of refraction Φ needed for total internal reflection [9]. Comparison of the lattice constants (e.g. see Ref. [6] and the material above) shows that their difference amounts to about one-thousandth and, hence, results in insignificant internal stresses between the core and cladding. This leads to the important conclusion that an isotopic medium constitutes a promising material for optoelectronics (the production of various integrated circuits) and, in particular, for manufacturing optical fiber.

Another no less important application of isotope engineering are isotope superlattices, the idea of which was proposed by Haller [4] in 1990. The main reason for studying superlattices is their one-dimensional nature, which makes localization of phonons (electrons) possible despite the small difference in the masses of the isotopes employed. For instance, the presence of a thin layer of the isotope ^{70}Ge placed inside the bulk of a material manufactured from the isotope ^{74}Ge always results in the appearance of a local vibrational mode whose frequency is higher than the ultimate vibrational frequency of the ^{74}Ge isotope. The first experimental studies of the Raman spectra of germanium superlattices with periods $2 \leq n \leq 32$ were carried out by Spitzer et al. [10]. In that paper the researchers also compared the experimental Raman spectra with the theoretical spectra (Fig. 2). Adequate agreement between the two sets of data is clearly visible. Notice that the theoretical model incorporated the mixing of two monolayers forming the interface. The number of peaks observed in the Raman spectra was found to correspond to the various ‘confined’ modes that preferably emerge in layers of the ^{70}Ge or ^{74}Ge isotopes. The results of Spitzer et al. [10] showed that isotopic samples of superlattices are an ideal model system for studying the confinement of optical phonons in superlattices, as also shown in Haller’s review [4].

We also note in passing another important application of an isotopically pure semiconducting germanium crystal. As is well known, just this material can serve as a detector of radiation with a broad sensitivity region that encompasses a range extending from infrared radiation to γ radiation. Noise (what is known as ‘spikes’) and the signal background are often due to the capture of cosmic radiation by the nuclei of the crystal-forming particles (neutrons, protons), which is

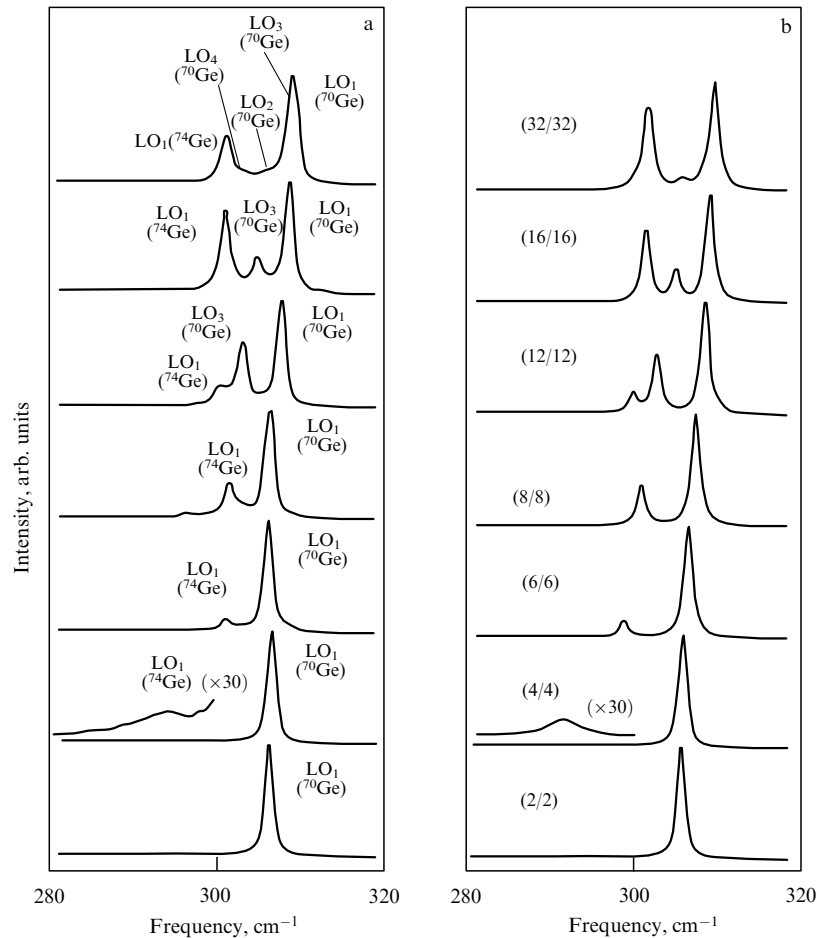


Figure 2. Measured (a) and calculated (b) Raman spectra of a series of isotopic $^{70}\text{Ge}_n/^{74}\text{Ge}_n$ superlattices. The spectra exhibit confined vibrational modes in layers manufactured from ^{70}Ge and ^{74}Ge isotopes [10].

followed by β decay. Clearly, the corresponding response will depend on the number of neutrons, in other words, on the type of nucleus, i.e. on the isotopic composition [11, 12]. It is also known that in the case of germanium these processes are strongest for the ^{70}Ge isotope [11]. By way of example Fig. 3 depicts, for the 10–250-keV range, the signal background of the response of detectors manufactured from natural germanium and from the ^{70}Ge isotope [12], i.e. what can be called the ‘dark’ signal. Clearly, the background level is much lower in the case of a detector manufactured from the ^{70}Ge isotope than in the case of a detector manufactured from natural germanium. It is the use of a detector manufactured from isotopically pure germanium that substantially increases the detector’s sensitivity (for more details see Refs [11, 12]).

3. Generation of light in isotopically mixed media

In recent decades the area of application of isotopically mixed media based on lithium hydride has broadened substantially. In addition to the traditional employment of this material in nuclear engineering [13, 14], lately a number of other very promising applications have emerged. The most important one, which has been actively discussed in the scientific literature [15–17], has to do with the possibility of manufacturing, at fairly low pressures, an insulator–metal junction based on lithium hydride, with the metallic conduction band being ‘genetically’ linked to hydrogen (see also Refs [19, 20]).

The use of LiH (LiD) in initiating a thermonuclear reaction was quite unique. A medium based on lithium hydride is thought to be a promising medium acting as a target in laser-induced fusion [18].

Another application that will be discussed here in greater detail is related to the possibility of using an isotopically mixed medium (e.g. $\text{LiH}_x\text{D}_{1-x}$ or $^{12}\text{C}_x^{13}\text{C}_{1-x}$) as an oscillator of coherent radiation in the ultraviolet spectral range [21, 22]. To achieve this, the use of indirect electron transitions involving, say, longitudinal optical phonons was planned. Using indirect electron transitions involving phonons to degenerate coherent radiation in semiconductors was originally proposed by Basov et al. [23]. Kulevsky and Prokhorov [24] were the first to observe stimulated radiation using emission lines of LO phonon repetitions in CdS on two-photon excitation (see also Ref. [25]).

In allowing for the potential profile in mixed crystals one cannot completely exclude the possibility of lasing involving a phononless line of exciton luminescence [26]. The observation of emission lines of LO phonon repetitions in wide-gap insulators (see Refs [5, 21]) has made it possible to pose the problem of lasing in the ultraviolet spectral region via intrinsic electron transitions, where practically no solid lasers can be found. It is the high quantum yield of intrinsic (e.g. exciton) luminescence of pure crystals ($\text{LiH}_x\text{D}_{1-x}$ and $^{12}\text{C}_x^{13}\text{C}_{1-x}$) that ensures high energy extraction per unit volume of lasing material. Figure 4 depicts, as an example, the exciton luminescence spectrum of pure (LiH and LiD) and

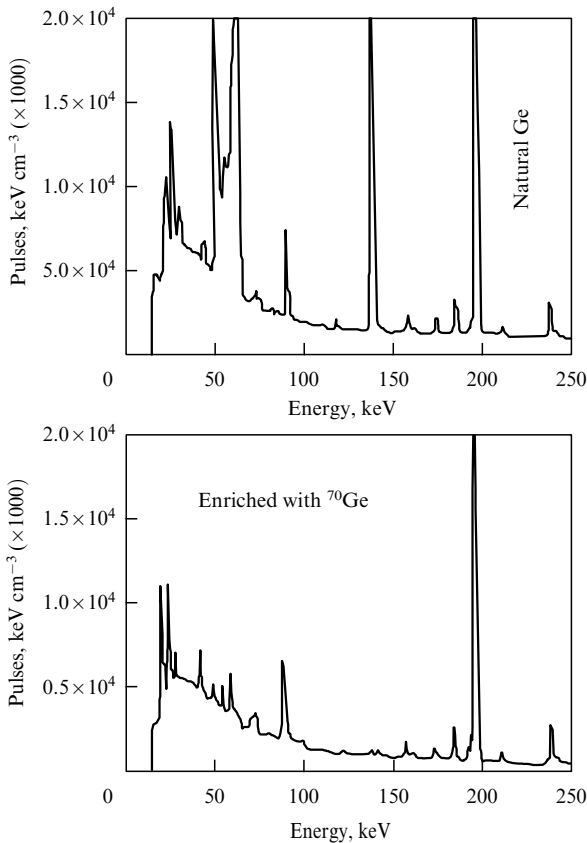


Figure 3. Spectral distributions of the signal background of the response of detectors made from natural germanium and from germanium enriched with the isotope ^{70}Ge (according to Ref. [12]).

mixed ($\text{LiH}_x\text{D}_{1-x}$) crystals at a low temperature. A common feature of all three spectra is a phononless emission line of free excitons and its 1LO and 2LO phonon repetitions. An increase in the density of the exciting light causes a burst of the radiation energy in the long-wave wing of the emission lines of the 1LO and 2LO repetitions (Fig. 5) at a rate that is higher for the 1LO repetition line [21]. A detailed dependence of the luminescence intensity and the shape of the 2LO repetition line is presented in Fig. 6.

The above results suggest that, as the excitation density increases, there emerges firstly a slight narrowing followed by a splash of a fine (and probably mode) structure — a phenomenon observed many times in semiconducting crystals [25]. Such a nonlinear and probably threshold dependence of the luminescence intensity on the excitation density with an observed fine structure suggests that there occurs lasing in these crystals. And since, for variations of the concentration of the isotopes (H or D), the frequency of the observed radiation ‘follows’ these changes in the isotope concentration, in this manner it is easy to achieve a conversion of the observed radiation in the 4.5–5.1-eV range (for more details see Ref. [27]) with $\text{LiH}_x\text{D}_{1-x}$ crystals, while with $^{12}\text{C}_x\text{^{13}C}_{1-x}$ crystal the size of the spectral transformation is about 15 meV.

4. Isotopic information storage

With every year the information aspects of physical processes are more frequently becoming a subject of basic research. Many of these aspects are based on ideal thought experiments

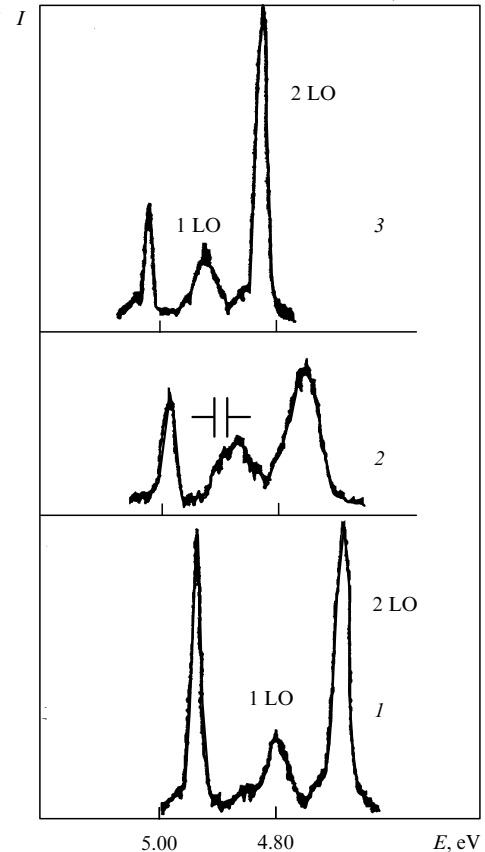


Figure 4. Photoluminescence spectra of free excitons at 4.2 K: 1, LiH; 2, $\text{LiH}_x\text{D}_{1-x}$; 3, LiD [5].

involving a single particle. This may be a particle of an ideal gas, a Brownian particle, etc. Of course, of no less interest from this viewpoint are condensed media (e.g. see Refs [28–30] and references cited therein). So far the practical aspect of this problem has been centered around the urgent need to create a scientific basis for the development of nanotechnology, which, in particular, would make it possible to produce the functional elements of microelectronics in the nanometer range. Fundamentally, the study of the information aspect of the mechanism answering for the formation of nonequilibrium structures is a logically inevitable element in the further development of the physics of condensed media.

Modern clusters (a unit for information storage) of interest usually contain a limited (very large) number of atoms $M \leq 10^4$. Indeed, using the conventional methods of physics and chemistry, one cannot obtain an exact copy of a macroscopic ($M \leq 10^4$) system. For instance, samples of glass of the same composition, synthesized in absolutely identical conditions of heating and nonequilibrium cooling of the melt, have practically identical macroscopic properties but are not exact copies of each other (see also Ref. [30]). It should be noted in this connection that further miniaturization of electronic circuits lies in the area of isotope engineering. It is in this area that the limit of information capacity is no longer determined by the size of the (still macroscopic) cluster [30] and can be reduced to atomic dimensions. In this case the information capacity limit is determined by the density of the crystal-forming particles (isotopes).

Indeed, information storage can be realized in the form of a zero or one corresponding to a single isotope placed within a

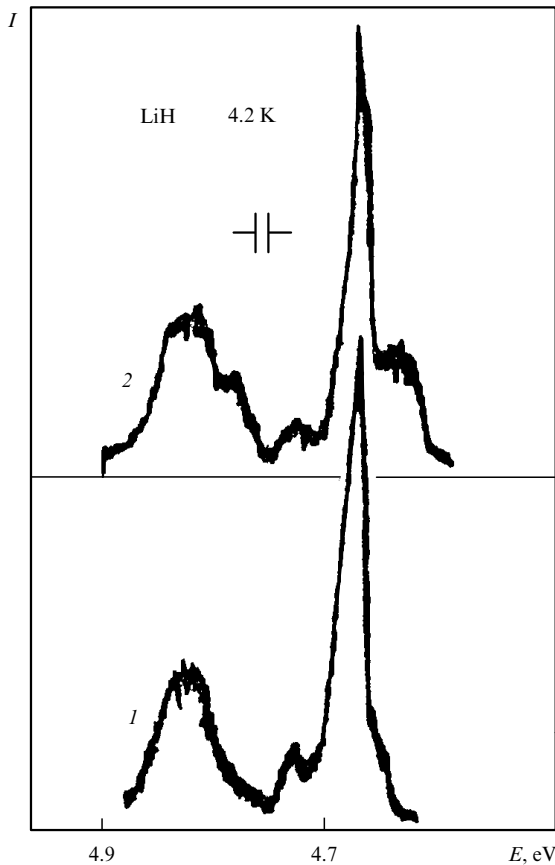


Figure 5. Luminescence spectra of free excitons in LiH crystals in the region of the emission lines of 1LO and 2LO phonon repetitions at 4.2 K for low (1) and high (2) densities of excitation of 4.99-eV photons. The scales of the curves are different [27].

bulk (thin-film) crystalline structure. Such techniques of recording and storing information could lead to a very high density of data storage ($\sim 10^{20}$ bit cm^{-3}), comparable to the number of the structure-forming particles per cubic centimeter. For instance, in contrast to a two-isotope system (^{12}C , ^{13}C), the utilization of a three-isotope system (^{28}Si , ^{29}Si , ^{30}Si) can directly lead to three-color images, since it is a well-known fact that visible light can easily be produced by combining (in proper proportions) three colors, but not two (see also Refs [6, 7, 31]).

5. Neutron transmutation doping

The method of neutron transmutation doping (NTD) in semiconductors is based on nuclear transformations of isotopes entering into the composition of semiconducting materials (not only such materials either) when the former capture slow (thermal) neutrons [32, 33]. To carry NTD, the samples of the semiconducting crystals are irradiated with neutron fluxes in nuclear reactors. When a neutron is captured, the given isotope becomes a different isotope with a mass number that is one unit greater:

$$\Phi \sigma_1 C_{(Z)N}^A = C_{(Z)N}^{A+1}, \quad (6)$$

where Φ (cm^{-2}) is the integrated flux (dose) of the thermal neutrons; σ_1 (cm^2) is the thermal-neutron capture cross section for the given isotope; $C_{(Z)N}^A$ and $C_{(Z)N}^{A+1}$ are the

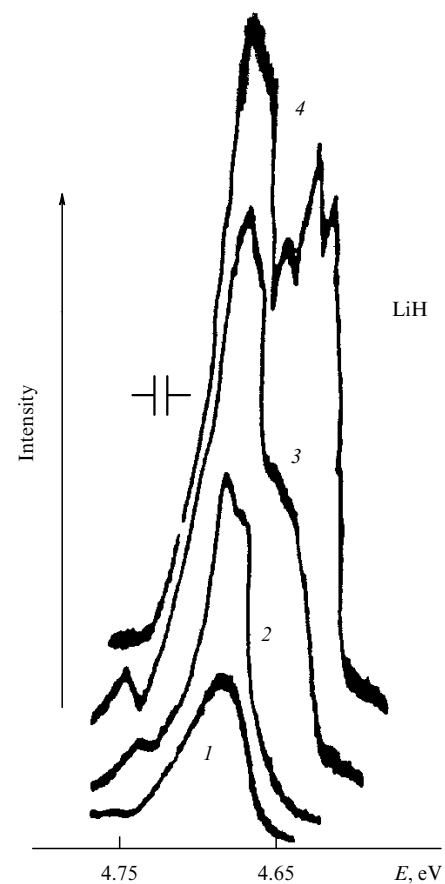
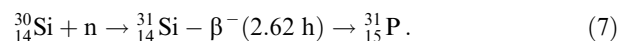


Figure 6. Dependence of the shape of the 2LO repetition line on the excitation density [27]: 1, $0.05I_0$; 2, $0.09I_0$; 3, $0.40I_0$, and 4, I_0 .

concentrations of the initial and final reaction products, respectively; Z is the nuclear charge, and A is the mass number. If the resulting isotope $^{A+1}_{Z}N$ is stable, such a reaction does not lead to doping.

Reactions in which the new isotope is unstable are the more interesting ones. Then after a certain time interval known as the half-life τ_1 , the isotope becomes the nucleus of a new element with a nuclear charge that is one unit greater, $^{A+1}_{Z+1}N$, in the case of β -decay or one unit smaller, $^{A+1}_{Z-1}N$, in the case of electron capture [33]. As an example, here is the equation of the reaction that leads to the appearance in silicon of a donor admixture of phosphorous [32]:



The interest in NTD can be explained by the two main advantages of this method over ordinary metallurgical methods of introducing impurities [4]. First, the high accuracy of this type of doping, since the concentration of the introduced impurities in the event of a constant neutron flux is proportional to the irradiation time, which can be controlled very accurately. Second, the high uniformity in the impurity distribution, which is attributed to the random distribution of the isotopes, the small capture cross section σ_1 , and the uniformity of the flux. Since $\sigma_1 \sim 10^{-23} - 10^{-24} \text{ cm}^2$, it is obvious that with maximum thermal-neutron fluxes in modern nuclear reactors and reasonable irradiation times the concentration of the phosphorous impurities introduced into silicon amounts to several units multiplied

by 10^{15} cm^{-3} , which, however, is quite sufficient for a number of important applications, especially in the production of high-voltage diodes and thyristors [32].

As for germanium, thanks to the large values of σ_1 and the presence of the active (for NTD) isotopes ^{70}Ge , ^{74}Ge , and ^{76}Ge , it is possible to dope relevant samples up to the transition to the metallic conduction state ($\sim 3 \times 10^{17} \text{ cm}^{-3}$), which makes it possible, on the one hand, to study the NTD process in germanium as a key to solving the fundamental problems in the impurity band (see also Ref. [34]) and metal–insulator transitions [35] and, on the other hand, to propose a number of applications as low-temperature resistance thermometers (thermistors) and radiation detectors [4]. Notice that these devices are also used in neutrino physics and in research concerned with the search for the ‘hidden mass’ in the Universe [36]. It must also be added that the main feature of NTD in germanium is that both acceptors (the majority impurity) and donors (the minority, or compensating, impurity) are introduced into samples in the doping process. Research dealing with the fabrication of multilayer structures based on the alteration of the two isotopes, ^{70}Ge and ^{74}Ge , in Si/Si $_{1-x}$ Ge $_x$ heterojunctions or the three isotopes, ^{70}Ge , ^{72}Ge , and ^{74}Ge , in a purely germanium structure with subsequent NTD has great potential. The latter structure will lead to the creation of $p-i-n$ -superlattices, and the main feature of the method used in such a process is that the growth of the superlattice and the doping process are separated. In ordinary epitaxial methods these processes are combined, which results in a mutual negative effect: the smearing of the transition boundary due to ‘flotation’ of impurities during a layer growth, and the increase in the number of defects in the growing layer due to the effect of the impurities in that layer. In the isotopic method the layers are grown without impurities and must have a perfect structure (see Section 2), since chemically the germanium isotopes are identical. Subsequent doping by the NTD method and defect annealing are conducted at a fairly low temperature, so that there is no transition boundary smearing and the structure of the layers does not deteriorate (see also Ref. [6]).

NTD is probably the simplest method for obtaining a uniform distribution of a neutral impurity over the bulk of a semiconducting crystal [37]. In addition to the applications mentioned earlier it must be noted that isotopic substitution opens new possibilities in solving the fundamental problems of solid-state physics, namely, the study of scattering of carriers by a neutral impurity, which, as shown by A Ansel'm more than half a century ago (see Ansel'm's textbook [39]), is an extremely important problem. At the same time it must be emphasized that, according to Koteles et al. [40], one of the mechanisms responsible for the doublet nature of polariton emission (including the case of isotopically mixed crystals [5]) is the scattering of polaritons by a neutral impurity (donor).

6. Diffusion in isotope heterostructures

Thermal vibrations of atoms in solids mainly present vibrations with a small amplitude near their average positions in equilibrium. However, due to the interaction of the atoms with their neighbors, the kinetic energy of the atoms does not remain constant. Even in the case where the average kinetic energy of the atoms is low, some of the atoms have, according to the Maxwellian distribution of atomic velocities in the crystal, fairly high energies. Such an atom may leave its equilibrium position and, overcoming the potential barrier

created by its neighbors, may find itself in a new free position of equilibrium. In the process the atom loses excess energy, which is transferred to the atoms of the crystal lattice. After some time the atom may again acquire enough energy to leave its new position and go over to the neighboring position of equilibrium. It is such displacements of atoms caused by thermal motion that constitute the basis for diffusion processes in solids. Atomic diffusion is the simplest one and its laws have been thoroughly studied. The simplest form of atomic diffusion is a self-diffusion, i.e. the displacement of atoms of crystal-forming particles within their own crystal lattice. Such a random walk, the diffusion of particles, is described fairly well by Fick's first law [41]

$$J = -D \frac{dN}{dx}, \quad (8)$$

where J is the flux of the diffusing particles, dN/dx is the concentration gradient, and D is the diffusion coefficient, which in many (but not all) cases is adequately described by the model with a thermal barrier E :

$$D = D_0 \exp\left(-\frac{E}{kT}\right). \quad (9)$$

Here D_0 is a constant. The diffusion of an impurity in semiconducting materials plays a key role in the production of electronic devices.

The last ten years have seen considerable progress in understanding the micromechanisms of the diffusion process due to the study of isotope heterostructures. The first results in self-diffusion of gallium in the isotope superlattices GaAs were obtained by Tan et al. [42]. To solve the problem, the researchers grew the superlattice roughly 1000-Å thick from the layers of pure $^{69}\text{GaAs}$ and $^{71}\text{GaAs}$, since As has no isotopes. The concentration profiles of the various isotopes were measured by ion mass spectrometry. Similar experiments were conducted later by other researchers (see Refs [4, 43] and the references cited therein). As an example, Fig. 7 depicts the profiles $C(x)$ of ^{69}Ga and ^{71}Ga in GaP isotope layers annealed at 1111 °C over the course of 231 min.

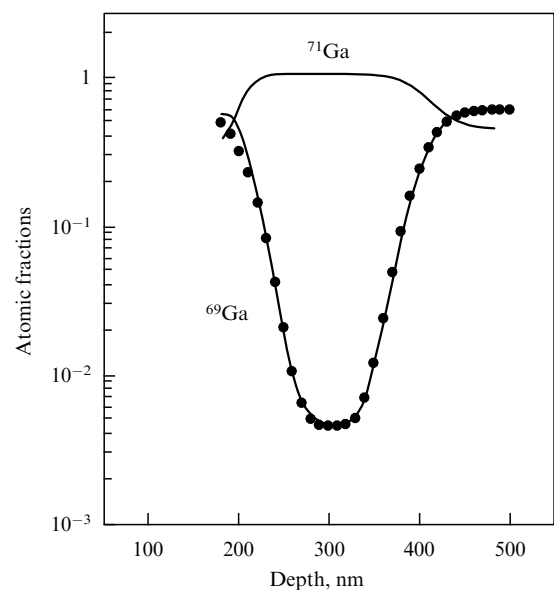


Figure 7. Concentration profiles of the isotopes ^{69}Ga and ^{71}Ga in GaP [44] (see the main text).

Figure 7 also presents the results of calculations of $C(x)$ for ^{69}Ga (dots) and ^{71}Ga (solid curve). Clearly, the agreement is reasonably accurate. This implies that self-diffusion of isotopes is described by Fick's law fairly accurately, which in turn implies that self-diffusion of gallium isotopes is accompanied by the movement of one simple intrinsic defect. The enthalpy and entropy of the diffusion process have reasonable values (~ 4.5 eV and 4 kV, respectively [44]).

In conclusion of this section it must be noted that the study of diffusion in isotope heterostructures has a number of important advantages over common methods:

- (1) the absence of surface effects;
- (2) the very different values of $C(x)$ for the majority and minority isotopes, and
- (3) the use of NTD in studies of such heterostructures makes it possible to investigate simultaneously self-diffusion and diffusion proper.

These differences obviously have a very promising future in the employment of isotope engineering in studies of diffusion processes in solids.

7. Isotope structures as an object of basic research

Isotopic substitution has made it possible to produce the objects of research that earlier were simply inaccessible (with the exception of the LiH–LiD system). The use of such objects allows the investigation of not only the isotope effects in lattice dynamics (elastic, thermal, and vibrational properties [3, 4, 6]) but also the influence of such effects on the electronic states (the renormalization of the band-to-band transition energy E_g , the exciton binding energy E_B , and the size of the longitudinal–transverse splitting Δ_{LT} [5]).

Furthermore, it is a well-known fact that the boiling temperature of ordinary and heavy (D_2O) water differ by several degrees. For heavier (as compared to hydrogen) elements, the difference in the melting (or boiling) points ΔT is much smaller, but still can be observed with modern methods. It is amazing, however, that there is practically no mention in the scientific literature of measurements of this difference (see also Ref. [7]).

Another remarkable fact is the strong dependence of the phase transition temperature (~ 200 K) on the isotopes Ba and Ti in BaTiO_3 [45]. The reasons for this selective anomaly have yet to be established.

8. Other potential applications of isotope engineering

Here is a short list of additional possibilities presented by isotope engineering:

- (a) The utilization of the differences in the temperature dependence of the thermal conductivity between pure and isotopically mixed materials in studies of phenomena associated with the focusing of phonons, precision thermometry, etc. (for more details see Refs [3, 4, 6]);
- (b) The use of isotopically mixed Ni films in neutron interference filters (these have already been applied by Antonov et al. [46]);
- (c) Isotopically mixed light emitting diodes, lasers, and other optoelectronic devices;
- (d) Acoustoelectronic gadgets and devices that take into account the fact that the speed of sound is proportional to $\sim M^{-1/2}$ and, hence, depends on the isotopes, and

(e) The use of the isotope boundary for Mössbauer filtration of synchrotron radiation, since this makes it possible to get rid of the background noise caused by the interaction between synchrotron radiation and the electrons in matter (for more details see Ref. [47]).

The applications discussed in this brief review and many others that are difficult even to envisage today make isotope engineering a very promising technology.

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