MECHANICS OF DAMAGE TO RUBY CRYSTAL BY LASER RADIATION

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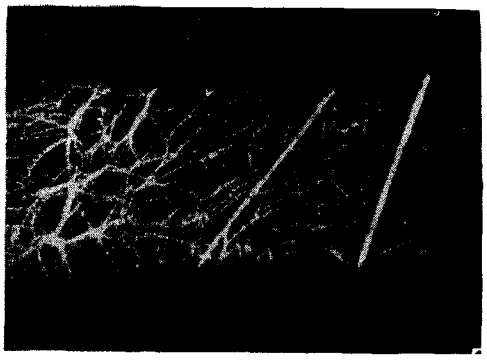
Many papers on the damage to ruby crystals by laser radiation have been published by now. However, the question of the decisive mechanism of internal damage remains debatable. In particular, the explanation that the damage is due to cascade ionization of the crystal matrix [1, 2] can hardly be regarded as fully adequate, since the experimental values of the threshold differ widely (by up to 100 times) [3]. Such a spread apparently indicates that impurities or structure defects play an important role in the mechanism of laser damage to ruby, but no serious attention has been paid to this fact in the literature to date.

We have therefore undertaken a study of the influence of various impurities on the threshold of damage produced inside a ruby crystal by giant laser pulses. The results show that the damage threshold depends strongly on the state of the impurities in the crystal lattice, and that the most harmful are impurities contained in the crystal in the form of inclusions of a foreign phase. The presence of such inclusions in ruby crystals indeed determines the threshold of the internal damage.

We have investigated ruby and sapphire crystals, grown by the Verneuil method, into which titanium, vanadium, iron, cobalt, nickel, and magnesium impurities were introduced. The impurity concentrations in the samples ranged from 10^{-3} to 10^{-4}%.[1)] We chose these elements because they are usually present in ruby-laser crystals. Depending on the growth conditions and subsequent heating of the crystals, these impurities can change valence and form a foreign phase (inclusion).

The valence state of the impurities was altered by high-temperature heating (up to T ≈ 1800°C) of the crystals. The valence state of an impurity entering isomorphically in the lattice was determined from the optical absorption and luminescence spectra. We used also ultramicroscopy in scattered light to determine the presence of foreign phases (inclusions) that might have been produced by the introduced impurities. Such a method has made it possible to detect the presence of individual particles of dimension $a \gtrsim 3 \times 10^{-6}$ cm in the crystal.



Distribution of nickel inclusions in a sapphire crystal, as seen in an ultramicroscope.

It was observed that in sapphire crystals heated in vacuum the titanium impurity is in the state Ti^{3+} and replaces isomorphically the Al^{3+} ions. When heated in an oxygen atmosphere, the titanium goes over into the Ti^{4+} state in which case some of the ions form a foreign phase (inclusions), the rate of precipitation of which increases sharply with increasing temperature. The structure of such a phase remains unclear; it

[1)] We note that such impurity concentrations do not exceed by more than one order of magnitude the contents of uncontrollable impurities, and were chosen to reveal clearly the role played by a concrete impurity in the damage mechanism.

can only be assumed to be either TiO_2 or aluminum-titanate.

Nickel, cobalt, and iron impurities in sapphire heated in an oxygen atmosphere form trivalent ions that replace Al^{3+} isomorphically. When these samples are heated in vacuum, the ions go over into a divalent state, with some of the ions entering isomorphically into the sapphire lattice, and some precipitated in a foreign phase. Ultramicroscopy investigations of this phase have shown that the inclusions are precipitated mainly on block boundaries, dislocations, and vacancy clusters (see the figure). A microscopic x-ray phase analysis of the precipitated particles has shown that the Ni, Co, and Fe impurities can be reduced all the way to the metallic state.

In samples with magnesium as the impurity, heating in an oxygen atmosphere produces a foreign phase in the form of minute inclusions that disappear after subsequent heating in vacuum.

No foreign inclusions are produced in sapphire with vanadium impurity; only $V^{2+} \rightarrow V^{3+}$ valence transitions occur when the annealing is in oxygen rather than in vacuum.

We note that the valence transitions of the impurities and the precipitation of the foreign phase are fully reversible under changes in the annealing atmosphere.

The damage occurring in the interior of ruby and sapphire samples with the indicated impurities was investigated by applying giant pulses ($\tau \sim 40$ nsec) from a ruby laser. The damage thresholds P_d of samples with different impurities were measured relative to the threshold $P_d^{(0)}$ of a control impurity-free sapphire sample (see the table), with the laser operating in the multimode regime. An estimate of the damage threshold of the control sample under the influence of radiation from a single-mode laser yielded a value $\sim 2 \times 10^{10}$ W/cm^2. We note that analogous results are obtained also for ruby crystals containing the same impurities.

Relative damage thresholds ($P_d/P_d^{(0)}$) of sapphire samples with different impurities at different annealing temperatures

Anneal. atmosphere \ Impurity	Ti	V	Co	Ni	Fe	Mg
Oxygen	$3 \cdot 10^{-2}$	$5 \cdot 10^{-2}$	0.5	0.6	0.6	$6 \cdot 10^{-2}$
Vacuum	0.8	$7 \cdot 10^{-2}$	10^{-2}	$2 \cdot 10^{-2}$	10^{-2}	0.9

An analysis of the results shows that a sharp decrease in the threshold of internal damage occurs (by up to a factor of 50) in those cases when a foreign phase is precipitated in a sapphire crystal, whereas in the absence of foreign inclusions all the investigated samples, both sapphire and ruby, have almost the same P_d, regardless of the difference between the introduced impurities and their valence states. The latter is apparently connected with the fact that the crystals contain minute ($a < 3 \times 10^{-6}$) inclusions of foreign phase, due to uncontrollable or introduced impurities, which could not be resolved by our ultramicroscope. The presence of inclusions of this kind is evidenced by the noticeable Rayleigh scattering, the intensity of which in the samples investigated by us greatly exceeded the intensity of the components of the thermal Mandel'shtam-Brillouin scattering.

The foregoing data indicate that inclusions play an important role in the mechanism of laser damage of ruby crystals. The decisive mechanism of damage of real crystals is apparently connected with the presence of absorbing inclusions. It must be emphasized that the problem of inclusions is more serious in crystals than in glasses, in view of the low solubility of many impurities in crystals and in view of the presence in the latter of structure defects that facilitate the formation of foreign-phase inclusions.

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ANGULAR DISTRIBUTION OF PROTONS IN THE REACTION $Li^6(e, e'p)He^5$ AT ELECTRON ENERGY 1158 MEV

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We measured the angular distribution of protons knocked-out by 1158-MeV electrons from the 1p and 1s shells of the Li^6 nucleus. We have compared the experimental data with shell-model calculations with an oscillator potential.

We have previously measured the cross section of the reaction $Li^6(e, e'p)He^5$ as a function of the missing energy $B = k_0 - k_1 - T_p - T_N$, where k_0, k_1, T_p, and T_N are the energies of the initial and final electrons and the kinetic energies of the proton and of the residual nucleus, respectively. The cross section has two well-separated peaks at $B = 3.5 \pm 1$ MeV and $B = 19 \pm 1$ MeV, corresponding to the production of the He^5 nucleus in the ground state with excitation energy 16.7 MeV.

We present here the results of a measurement of the angular distribution of the protons in the $Li^6(e, e'p)He^5$ reaction at the two aforementioned values of the missing energy B.

The measurements were performed with an electron beam of energy 1158 ± 3 MeV from the linear accelerator of the Physico-technical Institute of the Ukrainian Academy of Sciences at a constant angle of registration of the secondary electrons (20° in the lab) and at a constant proton momentum (396 MeV/c). The energy of the secondary electrons was adjusted to make the missing energy equal to 4 and 20 MeV. The secondary electrons and protons were momentum-analyzed with two magnetic spectrometers [1] with solid angles 1.3×10^{-3} and 2.4×10^{-3} sr, respectively.

To register the electrons we used a three-channel telescope with a momentum coverage 0.4% per channel and with a distance 0.6% between neighboring channels; the protons were registered with a telescope with a momentum coverage 3.12%. The coincidences of the signals of each of the three channels of the electron telescope with the signal from the proton telescope, as functions of the proton emission angle θ_p, were registered with time-amplitude converters.

In the momentum plane-wave approximation, the cross section of the (e, e'p) reaction is proportional to the cross section for the scattering of an electron by a proton moving with momentum $\vec{q}$, and to the square of the wave function of