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EVALUATIONS OF DIFFERENT METALS FOR MANUFACTURING MIRRORS OF THOMSON SCATTERING SYSTEM FOR THE LHD DIVERTOR PLASMA

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ABSTRACT

We compared various metals which is to be used as Thomson-scattering-laser-guiding mirrors in the Large Helical Device (LHD) plasma, in views of reflectivity, resistance to the long-term sputtering by low energy charge exchange atoms and to multi-shot laser-induced damage. Gold and rhodium mirrors, which are superior in high resistance to sputtering of charge exchange atoms and in high reflectivity, will be destroyed in 10^4 LHD-plasma shots; molybdenum, which is inferior to gold and rhodium in the sputtering resistance and reflectivity, will survive up to 10^6 LHD-plasma shots.

Keywords: metal mirror, Thomson scattering, charge exchange, laser induced damage, Large Helical Device

1. Introduction

Mirrors of the laser scattering system for the LHD (Large Helical Device) divertor plasma have to be located in the nearest vicinity of the outer divertor x-point [1]. Due to their location, the mirrors will be bombarded with charge exchange (CX) atoms. This can lead to an increase of roughness of the mirror surface and, consequently, to a decrease of the laser-induced damage threshold (LIDT) of the mirrors resulting in shortening the operation time of mirrors. The rate of mirror degradation will depend on the properties of a material, i.e., how fast the surface roughness (and, correspondingly, the absorption of the laser) will be increased under influence of both factors: charge exchange atom flux and multi-shot laser irradiation. Similar situation can occur in any large fusion device if there is a need to install laser mirrors close to the main plasma, inside the vacuum vessel where they can be subjected to CX atom bombardment.

Nowadays there are enough published data to analyse such a situation and make the conclusion towards possible materials that could be evaluated for manufacturing these plasma facing "first laser mirrors". Using the data available we shall compare the different candidate materials concerning resistance to the long-term sputtering with low energy (several hundreds eV) CX atoms and to multi-shot laser-induced damage. We will concentrate on those metals which have a rather high reflectivity at the wavelength 1064 nm that was chosen for the Thomson scattering system of LHD [1]. The list of such metals includes gold, silver, copper and aluminium that have the highest reflectivity values (R=0.94-0.98 at this wavelength) [2] and are widely used as mirror materials. However, all of them are far behind molybdenum, niobium, iridium, tantalum and tungsten from the view point of a resistance to sputtering [3]. Therefore being subjected to CX atom bombardment, the mirrors made of latter metals will keep their optical properties during longer period of time than mirrors made of metals with high sputtering yield. But at the same time, metals with high resistance to sputtering have a much lower values of initial reflectivity (R=0.67-0.87) in comparison with metals having the highest reflectivity. As a consequence, being used as laser mirrors they will absorb a higher portion of the laser beam energy, and this can be a reason for faster degradation of their optical properties. The optimum material for manufacturing first laser mirrors is to be found as a result of a compromise between demands to have high enough reflectivity and at the same time to have a small rate of erosion when being bombarded with CX atoms.

Among metals with low sputtering coefficient, molybdenum is probably the only one which has been investigated intensively as a laser mirror material. The correlation between optical and metallurgical properties of polished molybdenum mirrors was discussed in Ref. [4], and in a quite large number of publications ([5-8] and references herein) the resistance of molybdenum mirrors to single and multiple laser shots were investigated. However there are no publications devoted to the influence of ion bombardment on the laser induced damage threshold (LIDT) of laser mirrors.

In the present paper the analysis of influence of LHD experimental conditions on the surviving the first laser mirrors made of different metals was carried out with taking into account published data concerning the laser induced mirror degradation and recent results on the sputtering effects on optical properties of metallic mirrors.

2. Laser induced damage thresholds (LIDT)

There exist several threshold energy values for a high power laser beam interacting with the absorbing solid surface [5-10], and these values depend strongly on the mirror material and on the parameters of a laser beam. The important material characteristics are: its reflectivity (absorptivity) at the laser wavelength, thermal conductivity and diffusivity, yield strength, Poisson's ratio, Young's modulus and coefficient of thermal expansion. The important parameters of a laser beam influencing the final result of such interaction are: wavelength of the light, energy distribution in the beam cross section, beam time dependence, and total number of shots.

Despite a great number of publications which are concerned with laser beam interactions with solids, only two short reviews of LIDT can be indicated which were published as parts of books [9,10], but there is no review paper explicitly devoted to this subject. In this connection let us shortly analyse the results of several publications which have data that can be useful from the view point of the main aim of the present paper.

2.1. Single laser shot thresholds

Let us start from the simplest case and assume that the characteristics of a mirror do not change during the laser pulse except the temperature rises. Then, as long as the diameter of the probing laser beam is much larger than the maximum depth to which heat is conducted during the pulse time (the case typical for LHD experiments), the problem of heating becomes one-dimensional. Assuming a square wave duration t for the laser beam power, the surface temperature near the spot centre can be written as (for example, [10]):

$$T = T_0 + \frac{A \cdot I_0}{\sqrt{K \cdot \rho \cdot C}} \cdot \sqrt{t} \;, \qquad (1)$$

where T_0 is the initial surface temperature, I_0 is the beam intensity ($F = I \cdot t$ is the laser beam energy density) , A - optical absorptance (which, to a good approximation for a smooth surface, is 1-R, where R is the reflectivity), K - thermal conductivity, C - specific heat, ρ - density. Because this formula is based on simplified suppositions, it can be used with an acceptable accuracy for the estimations of the surface temperature rise when a laser beam interacts with a solid.

For more realistic cases, with not a square wave dependency on time but a Gaussian time dependence of the laser beam, and temperature dependent characteristics of the material, including the change of the reflectivity, this problem was solved by several authors [9, 11-13]. Analysing results of their own calculations, authors of [12] came to the conclusion that formula (1) gives much smaller error when the initial value of optical absorptance (at T_0) is high enough. This is connected with a relatively small increase of light absorption over its initial, already high value in the latter case. In the case when $A=1-R<<1$ the absorption increase can significantly exceed (up to several times [12]) its initial value if the surface temperature increases from room temperature to the melting point of the mirror material. For such cases, i.e., for metal with high reflectivity, the linear dependence of A versus temperature can be estimated in the form:

$$A(T) = A_0 + B \cdot (T - T_0). \qquad (2)$$

One of the first attempt to take into account the temperature dependence of optical absorption by the laser target to explain the experimental results was undertaken in [14]. Later on several authors used a similar approach with different details [9, 11-13].

The first theoretical study of the temperature dependency of the reflectivity was carried out by Ujihara [15]. Based on the Drude theory he calculated R(T) for three wavelengths (λ = 0.69, 1.06 and 10.6 μm) for metals which are frequently used as mirror materials: aluminium, copper, gold, silver. Fig.1 shows results of these calculations for λ=1.06μm (Fig. 11 from [15]). It is seen that for all metals discussed, the theory predicts a strong degradation of the reflectivity when the surface temperature rises. However, experimentally such a strong degradation was observed only by authors of [16] when Al and Cu samples were irradiated with a ruby laser. The absolute B values (in formula (2)) which can be found from data of the latter paper exceed significantly values published in other papers. For example, for copper mirror the values of B, which can be obtained from R(T) data of paper [16] in the range 300-1350K, are at the level $\geq 10^{-4}$/K in comparison to ~$2.2 \cdot 10^{-5}$/K and $3.4 \cdot 10^{-5}$/K from data presented for the same wavelength in papers [17] and [18], correspondingly. Values of A_0 and B (at λ = 0.488 and λ = 1.06 μm) for several metals are shown in Table 1, with B(Cu) at λ= 1.06 μm as an average meaning taken from several publications without taking account results of [16].

	λ = 0.488μm		λ = 1.06 μm	
Metal	A_0	B	A_0	B
Al	0.08	$0.9 \cdot 10^{-5}$*	0.06	$3.0 \cdot 10^{-5}$**
Cu	0.42	$3.4 \cdot 10^{-5}$*	0.03	$3.0 \cdot 10^{-5}$
Ag	0.06		0.02	$1.7 \cdot 10^{-5}$**
Nb	0.49		0.19	$2.0 \cdot 10^{-5}$***
Mo	0.41		0.33	$7.0 \cdot 10^{-5}$***
Ta	0.60		0.13	$4.0 \cdot 10^{-5}$***
W	0.52	$0.3 \cdot 10^{-5}$*	0.44	$1.5 \cdot 10^{-5}$***
Au	0.56	$3.8 \cdot 10^{-5}$*	0.02	$2.1 \cdot 10^{-5}$**

• - [18], ** - [11], *** - [19]

Table 1. Increment of optical absorption change for several metals with increasing temperature.

The lowest threshold for the irreversible change of the mirror surface subjected to the laser beam is connected with the appearance of slip lines on the mirror surface [5-8]. Authors of [20] found that the threshold for slip bands appearing on intrinsic copper is about five times lower than the threshold for melting. There is almost no influence of slips on the reflectance after low number of laser shots but they lead to faster decrease of reflectance during multiple-pulse exposure. As a result of slip phenomenon, the threshold for a multiple-pulse LIDT decreases significantly with increasing number of shots [8, 21-24]. We will discuss this in detail in the next section.

In papers [8], [21] and [23] phenomenological theoretical models were developed for the explanation of the slip phenomenon as a plastic deformation of the mirror surface under influence of the local heating in an area of a laser beam. The threshold values for the laser energy, F_0, were found by equalisation of the calculated sheer stress amplitude to the yield strength of the mirror material. But because of different approaches to the estimation of the effective forces in the area where the local heating of the mirror surface takes place, the results of calculations of LIDT for slips appearing are different for different authors. In approximation of the large laser spot size, formulas (20) from [24] and (16) from [21] give for the F_0 values:

$$F_0 \propto \frac{(1-\nu)}{(1-R)} \cdot \frac{C \cdot \rho \cdot \sigma}{\alpha \cdot E}, \tag{3}$$

$$F_0 \propto \frac{(1-\nu)}{(1-R)} \cdot \frac{\sqrt{K \cdot \rho \cdot C}}{\alpha \cdot E} \cdot \sigma. \tag{4}$$

In these formulas ν is the Poisson's ratio, σ- yield strength, α - the coefficient of thermal expansion, E is the Young's module, and other denotations are already explained earlier (C, ρ, K, 1–R).

Next LIDT which is necessary to be discussed here is the threshold for melting the mirror surface [5-8]. The melting phenomenon of laser irradiated metal surfaces was studied, probably, in much more detail than any other LIDT because it can be identified rather easily in experiments on laser beam - solid interaction.

The reason for the melting is the increase of surface temperature to the value exceeding the melting temperature of mirror material, due to absorption of ~ (1-R) portion of a laser beam energy. It follows from (1) that the threshold energy of a laser beam for melting the surface in every single shot (with fixed effective pulse duration) depends only on thermal and optical properties of mirror material:

$$F_m \propto \frac{(T_m - T_0)}{(1-R)} \cdot \sqrt{K \cdot \rho \cdot C}. \tag{5}$$

In approximation that R does not change with changing surface temperature the F_m value has to be proportional to $t^{0.5}$ and inversely proportional to an absorptivity of a material.

Several groups checked the correspondence of experimentally measured parameters F_0, F_m and those predicted by formulas (3)-(5). In some cases reasonable quantitative agreement was found [10], in others only qualitative agreement. In Fig. 2, as an example of qualitative agreement of experimental data with formula (5), we combine results of the LIDT magnitude for germanium (λ = 10.6μm, [25]) and copper [10] mirrors with different initial absorptance values (indicated along the X axis). This example shows that relation (5) can be used (together with Y/R criterion and formulae (3) and (4)) for estimating the suitability of different metals to be utilised for manufacturing laser mirrors for utilisation in such a hostile environment as a LHD one.

Metal	t, ns	LIDT, J/cm² slip	melting	R change	References
Cu	10	8.8	11.3		JOSA, B5 (1988) 648
	9	7.4	9		QE - 17 (1981) 2078
	0.15			0.4 - 0.6	NBS, SP, N 435 (1975) 29
	17			2 - 4	NBS, SP, N 435 (1975) 29
	11			2.9	NBS, SP, N 435 (1975) 29
	0.05			0.4	NBS, SP, N 435 (1975) 29
	11			2.1	NBS, SP, N 435 (1975) 41
	11			3.0	NBS, SP, N 435 (1975) 41
	40		6		APL, 6 (1975) 165
	22			10.4	QE - 19 (1983) 1482
	22			7.4	QE - 19 (1983) 1482
	22			6.5	QE - 19 (1983) 1482
	5	2.7			NBS, SP, N 669 (1982) 164
	5	2.5			NBS, SP, N 669 (1982) 164
	5	1.9			NBS, SP, N 669 (1982) 164
Al	7		2.7		AP, 25 (1981) 127
	10	0.6	3.0		JOSA, B5 (1988) 648
	0.15			4.0	NBS, SP, N 435 (1975) 29
Ag	9	5	10.5		JOSA, B5 (1988) 648
	22			5	QE - 19 (1983) 1482
Au	9	2.5	5.6		JOSA, B5 (1988) 648
Mo	10		1.55		AO, 30 (1991) 5239

Table 2. Threshold values for slips, melting or significant reflectivity change published in indicated references.

However, it is necessary to point that the coincidence between measured and calculated values of LIDT, observed in some experiments, looks rather unexpectedly if one takes into account the reflectivity change which has also been observed in several experiments. In addition to mentioned papers [15, 16] which presented such data, Fig. 3 shows dependencies of R on F_0, drawn from time dependencies of R for copper mirrors during single laser shots published in papers [26] and [27]. It can be seen that the decrease of R for copper mirrors during single laser shots published in papers [26] and [27]. It can be seen that the decrease of R starts already at low laser beam energy density, and in both cases it approaches 90% of the initial value at about the same energy density of laser beams (E~1J/cm²), inspite of a big difference between the reflectivity coefficients without laser irradiation: ~0.92 (at λ= 0.632 μm) and ~0.98 (at λ=1.06 μm), which one can calculate using optical constants for copper [3]. This value of laser beam energy density is several times lower than LIDT for melting observed in these and other experiments for copper mirrors irradiated at

λ=1.06 μm: 6 [26], 9 [28] and 11.3 [29] J/cm^2. The importance of results shown in Fig. 3 for LHD Thomson scattering measurements in a divertor plasma follows from the fact that the scale of the laser beam energy density in LHD has to be at the level of several tenths of J/cm^2 to realise the scheme discussed in [1]. Table 2 shows LIDT values obtained in conditions (wave length, pulse duration scale) close to the ones planned for the LHD measurements.

Other types of LIDT, i.e. for appearing pits, cracks or craters, the beginning of vaporisation, light or particle emission, - will not be discussed in the present paper. As a rule, the values of laser beam energy density required to induce these LIDT are higher than or comparable to the LIDT for melting [5,6,20,28,29].

Metal	ρ, g/cm^3	α, 10^{-6}/C	T_m, C	C_p, J/gC	K, J/cms C	E, Gpa	ν	A=1-R	σ_{02}, MPa
Al	2.7	24	660	0.9	2.2	70	0.31	0.06	22
Cu	8.95	17	1083	0.385	3.95	120	0.38	0.03	70
Mo	10.2	5	2625	0.256	1.465	315	0.31	0.33	570
Nb	8.7	6.8	2450	0.272	0.57	110	0.39	0.19	210
Ag	10.5	19.7	960	0.235	4.14	80	0.37	0.02	25
Ta	16.6	6.5	2990	0.15	0.55	190	0.35	0.13	400
W	9.26	4.3	3400	0.134	1.8	390	0.33	0.44	760
Au	19.3	14.2	1063	0.134	2.98	80	0.43	0.02	40
Rh	12.4	8.2	1966	0.248	1.51	385	0.26	0.18	85
Pt	21.4	8.8	1770	0.134	0.71	170	0.39	0.25	70
Ir	22.4	6.8	2450	0.13	1.48	550	0.28	0.21	95
Ni	8.9	13.3	1455	0.441	0.94	210	0.35	0.28	80
Os	22.5	4.6	3000	0.13	0.88	575	0.28	0.41	90
Pd	12.1	11.8	1554	0.244	0.72	120	0.39	0.19	60
V	6.2	7.8	1740	0.5	0.31	150	0.365	0.42	105

Table 3. Characteristics of metals used for calculating figure of merits of possible "first laser mirror" materials.

To compare the priorities of different metals to be the laser mirror materials, we compared the LIDT values for melting and the appearance of slips using all three formulas: (3)-(5). The characteristics of metals under discussion that have been used in these calculations are shown in Table 3. The data concerning some properties of the candidate materials (such as the yield of strength values) are very much different in different publications. Those presented in the last column of Table 3 have been recently published in [30]. The results of calculations, Table 4, are presented in different steps. Columns 2-4 contain the direct data of calculations using formulae 3-

5, as indicated, but relative to the data for copper mirror, i.e., some figure of merits (FOM) for all metals, and the next three columns contain distributions of places of every metal. To-day we have no definite base to prescribe the difference in an importance of any of these criteria. That is why in the 8-th column we have added the sum of the number of places for every metal given, which meansthat the statistical weights is taken equal for the results of calculations by all three formulae. In the second last columns we show the final data for all materials and, once again, the reflectance coefficients calculated based on optical constants recommended in [3].

Metal	F. (3), slip	F. (4), slip	F. (5), melting	Place, F. (3)	Place, F. (4)	Place, F. (5)	Σ	Total place	R $\lambda=1.06\mu m$
Au	1.065	1.062	1.11	1	2	2	5	1	0.98
Cu	1.00	1.00	1.00	2	3	3	8	2-3	0.97
Ta	0.72	1.65	0.20	3	1	4	8	2-3	0.87
Ag	0.61	0.50	1.15	4	7	1	12	4	0.98
Mo	0.57	0.81	0.12	5-6	5	9	19.5	5-6	0.67
W	0.57	0.73	0.13	5-6	6	8	19.5	5-6	0.56
Nb	0.4	0.87	0.11	7	4	10	21	7	0.81
Al	0.13	0.15	0.19	8	10	5	23	8	0.94
Rh	0.09	0.14	0.18	9	11	6.5	26.5	9	0.82
Pd	0.076	0.16	0.09	9	9	11.5	29.5	10	0.81
Ir	0.069	0.10	0.18	11	14	6.5	31.5	11	0.79
V	0.051	0.17	0.03	13	8	15	36	12	0.58
Pt	0.06	0.13	0.08	12	12	13.5	37.5	13	0.75
Ni	0.049	0.11	0.08	14	13	13.5	40.5	14	0.72
Os	0.037	0.07	0.09	15	15	11.5	41.5	15	0.59

Table 4. Figure of Merits for different metals to be a material of the "first mirrors" of laser diagnostics,calculated using formulae (3)-(5).

It is seen that number of metals suitable for manufacturing "first laser mirrors" is very limited. All three criteria of relative resistance of materials to laser-induced degradation of mirrors show that Cu, Ag and Au are staying almost at the same level and have distinctive advantages over most other metals tested. However, between these gold has much lower sputtering coefficient when being bombarded with hydrogen (deuterium) atoms [2]. These three materials, which are commonly utilised for manufacturing mirrors with high optical properties, are accompanied by: Ta, Mo and W, followed by Nb, Al, Rh, Pd, Ir, V, Pt, Ni and Os. In the next sections the role of sputtering effects in the distribution of priorities between these metals will be discussed in detail. Now we note that molybdenum, which is frequently used as a laser mirror material, occupies rather high place behind the first four metals, according to criteria (3)-(5).

2.2. Multiple-pulse laser-induced thresholds

When mirrors are subjected to multiple-pulse laser shots, as it will be in the case of LHD, the damage thresholds decrease significantly from the values typical for a single laser shot test [8, 22-24]. Fig.4 shows how the ratio of LIDT for repeated identical laser shots, F_N to LIDT for every single shot, F_1, decreases with increasing the number of shots, N, when mirrors made of Cu, Ag [23] and Mo [8] were irradiated at λ=1.06μm. In all these cases the frequency of the laser pulse repetition rate was 10 Hz, but in [22] qualitatively similar results were obtained with frequency of the laser pulses only 0.05 Hz (for λ=10.6 μm). This qualitative agreement is some indirect support of the hypothesis of the accumulation of defects created during every laser shot on the mirror surface, independent on the time interval between shots [8, 22-24], as a main reason of mirror degradation which is not connected directly with the gradual temperature rise from shot to shot. More direct evidence of this hypothesis follows from the agreement of measured and calculated displacements of the molybdenum mirror surface near the centre of a laser spot [8] during the shot, and also from measured and calculated dependencies of LIDT on the number of shots [8] as well as from qualitative coincidence between results of laser experiments and mechanical tests found in [8] and [24].

In spite of the big scattering of points in Fig.4a, it is seen from these data that there are observed two stages of LIDT dependence with very much different rates of LIDT change when the laser shot number increases. Initially, up to several hundreds shots, the LIDT value changes slowly with approximately equal exponent for Cu and Ag mirrors in log-log dependence: $F_N = F_1 \cdot N^{-0.04}$. The further increase of N leads to much faster rate of LIDT degradation, and exponents become to be different for both metals: ~(-0.3) for copper and ~(-0.16) for silver. Similar two-slope dependence on the number of shots was not found in [8] for Mo mirrors as Fig.4b shows, and in [22] for Cu mirrors. However, in the last case the total number of shots was only 150, i.e. lower than the shot numbers after which the change of a slope of F_N(N) dependencies in Fig.4a becomes to be evident.

The comparison of all three cases of Fig.4 shows that Mo mirror is more resistant to the multi-shot laser test than the copper mirror and it is a little more resistant in comparison to the mirror made of silver: the degradation of its LIDT can be described by the formula $F_N = F_1 \cdot N^{-0.12}$ [8].

For LHD experimental program there is a need to have more than one hundred laser shots per plasma pulse [1], and thus if one wants not to changing mirror properties during the operating time for ~10^4 plasma pulses, these mirrors have to survive $\geq 10^6$ laser shots in total. No one mirror has been tested for such number of laser shots up-to-now, so we must approximate results of tests with shot numbers which are two orders in magnitude lower. Using the data presented above, we can estimate that for a copper mirror the energy of every shot should be no more than 10% of the LIDT found in single shot tests, and for silver-on-copper mirrors the energy of every shot should not exceed ~20% of the one shot LIDT. For molybdenum mirrors [8] the value of LIDT for multiple-shot test is approximately on the same level: $F_N/F_1 = 0.19$ for $N=10^6$. This limit on the magnitude of laser beam energy for the multiple-shot mode of laser operation with 10^6 shot number (i.e., $F_N/F_1 \leq 0.1$-0.2) is very strict, if one takes into account the geometry of measurements [1]. It is not excluded that in practice the "first laser mirrors" must be changed after $\sim 10^5$ laser shots, with energy in every shot near ~10% of F_1 for copper and ~30% of F_1 for molybdenum and silver.

2.3. Change of LIDT with angle of incidence

In conditions of LHD experiments [1] there will be a possibility of some increase of LIDT for the "first laser mirrors" by utilising a polarised laser beam when doing Thomson scattering measurements in the divertor plasma. The reason for such an increase is the difference in the dependencies of light absorptivity by the mirror surface for parallel and perpendicular light polarisation on the incident angle, Θ: A_p is an increasing function of Θ, $A_p = A(0)/\cos\Theta$ and A_s is a decreasing function, $A_s = A(0)\cdot\cos\Theta$ (where Θ is counted from the surface normal). So, for a s-polarised laser beam (with the wave vector perpendicular to the plane of incidence) the LIDT will rise with inclination of the mirror to the beam direction for two reasons: due to increasing the illuminated mirror surface area (as $\cos^{-1}\Theta$) and secondly due to decreasing the mirror absorptivity. Thus: $F_{0s}(\Theta)=F_0(0)/\cos^2\Theta$. On the contrary, in the case of a p-polarised laser beam the increase of effective surface area just compensates the decrease of the absorptivity giving neither a positive nor a negative effect.

There are several publications on this subject, but the most informative are papers [22] and [31]. In the former one the results on $F_s(\Theta)$ dependencies at $\lambda=10.6\mu m$ for mirrors made of copper, molybdenum and stainless steel, and in the latter - similar dependencies at $\lambda=1.06\mu m$ for two copper samples. All these data are shown in Fig.5 in relative units, i.e., $F_{0s}(\Theta)/F_0(0)$, together with theoretical prediction for $F_{0s}(\Theta)$ dependence (solid line). The excellent conformity of experimental points to the behaviour predicted by theory is clearly seen, indicating that the utilisation of s-polarised laser beam can increase LIDT significantly if the mirror is illuminated at a grazing angle. In practice, due to constructive limitations, the angle of incidence of a laser beam can not be far over 45°, and therefore the LIDT gain will not be more than factor 2 as compare to LIDT for normal incidence.

3. Effect of sputtering

Sputtering of mirror surface due to bombardment with CX atoms can result in gradual change of the surface roughness and decrease of mirror reflectivity. In turn, the increase of laser beam energy absorption will lead to decrease of LIDT and shorten the time of mirror operation. The difficulties in the estimation of this effect are connected with almost total lack of data concerning the dependence of mirror quality upon the layer thickness sputtered with light ions: hydrogen or helium. Results obtained with heavy ions (e.g. [32] and references herein) cannot be utilised because of different ratio between rates of sputtering and defect accumulation in a near surface layer in both cases (in detail this problem was discussed in [33]).

Recently some data concerning the long-term sputtering effects on optical properties of mechanically polished stainless steel mirrors [34] and on diamond machined copper mirrors were obtained in Kharkov Institute of Physics and Technology. Mirror samples were bombarded in a reflex discharge with ions of deuterium plasma of a mean energy of ~650 eV and with a wide energy spectrum: of $\Delta E \approx 120$ eV. The dependency of reflectivity on the thickness of sputtered layer for two stainless steel and two copper samples are shown in Fig.6a and Fig.6b, correspondingly. In the stainless steel case one sample was preliminary bombarded with MeV energy range Cr^{2+} ions as an imitation of neutron irradiation [33].

The drastic difference between the results for these two materials is clearly seen. Mirrors made of stainless steel demonstrate rather low rate of reflectance change initially, and a fast drop of R was observed only after sputtering a layer $\geq 3\mu m$. At the same time, the reflectivity of copper mirrors started to decrease already at early stage of the sputtering procedure and ~10% drop of R at λ=600nm, as compare to its initial value, was observed after layer thickness ~0.1μm has been sputtered.

Such big difference observed in the behaviour of mirrors made of these two materials, under similar conditions of irradiation, show the importance to make a right choice for a mirror material from the view point of the long-term sputtering effects on the mirror properties. It is necessary to underline that the difference in the rates of R degradation for both materials is much higher than difference in values of the sputtering coefficient: the ratio Y(Cu)/Y(st.st.) does not exceed ~3 [2, 35]. This means that not only the low sputtering coefficient is important but also the resistance of a given material to the change of its initial surface roughness value during the long-term sputtering procedure. Important role in the resistance property can play the structure of mirror material, technology of its manufacturing and surface preparation, initial magnitude of a roughness, and so on.

Unfortunately, to-day such data are not known and therefore, as the first approximation and in contradiction with Fig.6, we shall suppose that for different materials the sputtering of the same thickness leads to an identical change of the surface roughness.

Based on Fig.6b data and taking account the wave length of a probing laser beam in LHD (1.06μm) let us choose as the critical thickness of a sputtered layer, equal to all metals in Table 3, the value 0.2μm, - after which the copper mirrors lost ~20% of their reflectivity at the wave lengths ≤ 0.6μm (Fig.6b). Then, for estimation of the sputtering rate, one needs to know the value of the CX atom flux density to the mirror surface and the mean energy of the CX atoms. To-date, the data most easily comparing to LHD conditions are data obtained in experiments on tokamak ASDEX being operated with a divertor [36], and on tokamak PLT [37] where measurements were done in poloidal cross sections located far from the poloidal limiter position. From these papers the CX atom flux density at the level $\geq 10^{15}/cm^2s$ can be taken as a starting point, and this value is in agreement with an estimation made for LHD vessel wall [38]. The mean energy of the CX atoms measured on ASDEX was in the range 300-600 eV [36]. Thus we will utilise the following characteristics of a CX atom flux bombarding the "first laser mirror" surface: $\Gamma_{CX} = 2\cdot 10^{15}/cm^2s$ and $\langle E \rangle_{CX} = 300eV$. The sputtering yield values for this energy are shown in Table 5 (second column) for the majority of metals from Table 4, excluding those ones which have lowest indices according to the criteria of eqs. (3)-(5).

As an example, the layer of copper with thickness 0.2μm contains $\sim 1.7\cdot 10^{18}$ of Cu atoms and it can be fully sputtered by $\sim 9.4\cdot 10^{19}$ of hydrogen atoms with 300 eV mean energy for $\sim 4.7\cdot 10^{4}$s of the total plasma exposure time, which corresponds $\sim 2.4\cdot 10^{4}$ number of plasma pulses of 2 seconds duration each. This number of pulses looks quite reasonable. But if with time the duration of every plasma pulse in LHD is increased to ≥10s and deuterium becomes the working gas, - it will take only $\sim 1.7\cdot 10^{3}$ plasma pulses to sputter a layer of ~0.2μm thickness on the copper mirror, and thus to lead to its destruction due to multiple-shot laser irradiation. These and similar data for other metals are shown in Table 5.

The data of this Table predict that Al, Cu and Ag mirrors cannot conserve their optical properties during 10^4 of 10s plasma pulses with deuterium as a working gas. The gold, rhodium, molybdenum and niobium mirrors are close to this conventional threshold pulse number, and only mirrors made of iridium, tantalum and tungsten can withstand in such conditions even during much larger number of plasma pulses.

Metal	Y(H)	Y(D)	Number of metal atoms in 0.2 μm layer	Time for 0.2μm layer to be sputtered with H atoms, s	Time for 0.2μm layer to be sputtered with D atoms, s
Al	$1.6 \cdot 10^{-2}$	$4.3 \cdot 10^{-2}$	$1.2 \cdot 10^{18}$	$3.7 \cdot 10^{4}$	$1.4 \cdot 10^{4}$
Cu	$1.8 \cdot 10^{-2}$	$5.0 \cdot 10^{-2}$	$1.7 \cdot 10^{18}$	$4.7 \cdot 10^{4}$	$1.7 \cdot 10^{4}$
Ag	$1.0 \cdot 10^{-2}$	$4.0 \cdot 10^{-2}$	$1.2 \cdot 10^{18}$	$6.0 \cdot 10^{4}$	$1.5 \cdot 10^{4}$
Pd	$3.6 \cdot 10^{-3}$	$1.9 \cdot 10^{-2}$	$1.4 \cdot 10^{18}$	$1.8 \cdot 10^{5}$	$3.6 \cdot 10^{4}$
Au	$5.0 \cdot 10^{-4}$	$7.5 \cdot 10^{-3}$	$1.2 \cdot 10^{18}$	$1.2 \cdot 10^{5}$	$8.0 \cdot 10^{4}$
Rh	$7.6 \cdot 10^{-4}$	$7.0 \cdot 10^{-3}$	$1.5 \cdot 10^{18}$	$1.0 \cdot 10^{6}$	$1.0 \cdot 10^{5}$
Mo	$2.0 \cdot 10^{-4}$	$2.5 \cdot 10^{-3}$	$1.1 \cdot 10^{18}$	$2.8 \cdot 10^{6}$	$2.3 \cdot 10^{5}$
Nb	$1.7 \cdot 10^{-4}$	$2.4 \cdot 10^{-3}$	$1.1 \cdot 10^{18}$	$3.2 \cdot 10^{6}$	$2.3 \cdot 10^{5}$
Ir	0	$8.0 \cdot 10^{-4}$	$1.4 \cdot 10^{18}$	∞	$9.0 \cdot 10^{5}$
Ta	0	$1.5 \cdot 10^{-4}$	$1.1 \cdot 10^{18}$	∞	$3.6 \cdot 10^{6}$
W	0	$1.2 \cdot 10^{-4}$	$1.3 \cdot 10^{18}$	∞	$5.5 \cdot 10^{6}$

Table 5. Estimated time for 0.2μm thickness layers of indicated metals to be sputtered with CX atoms of $2 \cdot 10^{15}/cm^2 s$ flux density and 300 eV mean energy.

4. Discussion and conclusion

Thus, the above presented analysis gives us a possibility to range mirror materials from view points of their resistance to the damage induced by repeated shots of a high energy laser beam and by sputtering with CX atoms, in the frame of accepted approximations. Concerning the first factor, the multi-pulse regime of mirror operation itself limits strongly the maximum power density of a laser beam comparatively to the LIDT found during a single shot test, depending on the maximum number of laser shots available. For $N=10^5$ shots the estimated level of laser beam energy should not overcome values of $\sim 0.1 \cdot F_1$ for copper and $\sim 0.3 \cdot F_1$ for silver and molybdenum mirrors, with F_1 been close to values indicated in Table 2. LIDT decrease in a multiple-shot case due to assumed equal degree of surface morphology change during long-term sputtering. Actually, the data bases on this subject were obtained only for few metals, as was indicated in the corresponding part of the text. The appearance in future of new data can correct these results. But using now-a-day data from publications on this subject, the priorities for metal to be a material for the "first laser mirror" also depend on the limit on the number of plasma pulses and consequently on the total number of laser shots. For the chosen conditions of LHD experiments [38] and the 10^4 upper limit on the 10s plasma pulse number, after which the laser mirrors can be changed (which corresponds to $>10^6$ laser shots), - gold and rhodium mirrors can be successfully used. If the upper limit on number of plasma pulses is 10^5, - molybdenum and tantalum should be placed on the first position. However, tantalum is not resistant enough against the oxidation process, and this was probably the reason for the low reflectivity of Ta mirror found in [27] for λ=1.06μm: R=0.51 in comparison to ~0.87 from [3]. It means that if there is no possibility to clean mirrors from the oxide film directly inside the LHD vacuum vessel, the mirrors made of tantalum probably cannot be used as the "first mirrors" of a laser diagnostics, and molybdenum will be the only candidate material.

Finally, in the case the construction of the device allows the "first laser mirrors" to be changed after every 10^3 plasma pulses - copper, silver and gold becomes to be the better materials according to the "figure of merits" calculated with taking account the sputtering effects on the mirror reflectivity.

Thus, we see that the very important criterion which was not separated but was practically used in estimations, is the number of plasma pulses (and, correspondingly, the laser shot number) that mirrors have to withstand in given environmental conditions of mirror operation. This number defines both the total exposure time of a mirror to the CX atom flux and the limit on the maximum power of a laser beam in every laser shot.

The approach shown here can be used for evaluating the prospect of any material to be utilised for manufacturing the "first mirrors" of laser diagnostics placed inside the vacuum vessel of a fusion device. As an example, we can reference on the project of the Thomson scattering scheme proposed for ITER [39]. In this case the "first laser mirror" has to be placed inside the vacuum vessel because the plasma facing window for transmitting laser beam made of any dielectric material, will lose its optical properties even much faster than a metallic mirror.

In conclusion, we must add several important remarks.

Authors of [40] found that slips in size comparable to other samples are not observed on the mirror surface made by metal film deposition on the perfectly polished substrate. In application to the main idea of this paper, it means that dependence of LIDT on the number of laser shots can be not so severe as Fig.4 shows, and the upper level of laser beam energy can be increased in some degree as compare to the limits, found from the approximation of data Fig.4 to higher number of laser shots, i.e., $\sim 0.1 \cdot F_1$

for copper and ~$0.3 \cdot F_1$ for silver or molybdenum mirrors in the case NÚ10^5.

Then, the role of carbon or boron film on the mirror surface was not discussed here. However, the appearance of such film on mirrors cannot be avoided not only because of boron-carbon coating of the vessel walls but also due to the utilisation of carbon-graphite materials for the protection of some parts of the inner construction elements from the direct plasma contacts (in the LHD - divertor plates made of carbon-based materials are planned to be used). This film can play twofold role: to protect the mirror surface from sputtering on the one hand, and to increase the absorptivity of laser beam energy on the other hand. So, the final result of the film appearing on the long-term behaviour of laser mirrors cannot be predicted without carrying out the dedicated experiments.

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Figure captions

Fig. 1. Reflectivity of several metals at λ=1.064 μm versus temperature of mirror surface [15].

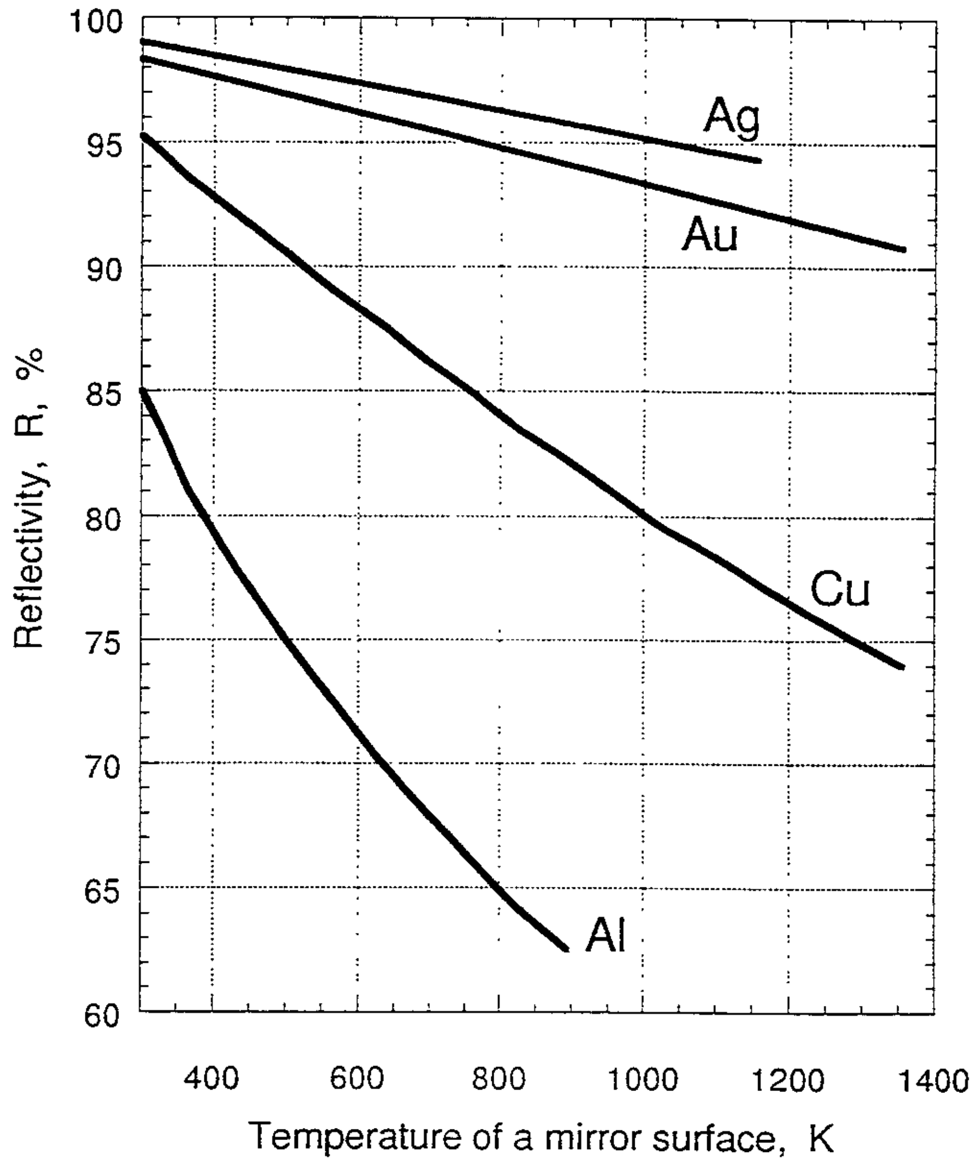
Fig. 2. Dependence of LIDT on the surface absorptivity of Ge at λ=10.6 μm [25] and Cu at λ=1.064 μm [10]. Lines show the A^{-1} dependencies.

Fig. 3. Dependence of reflectivity of copper mirrors during the laser pulse on the energy of laser beam for (a) λ=0.69 μm [26] and (b) λ=1.064 μm [27].

Fig. 4. Change of LIDT values with increasing number of laser shots for: (a) Cu and Ag [23] and (b) Mo [8].

Fig. 5. Change of LIDT for s-polarised laser beam versus angle of incidence, after [22] and [31].

Fig. 6. Dependence of reflectivity of (a) stainless steel and (b) copper mirrors on the thickness of layer sputtered by ions of deuterium plasma.



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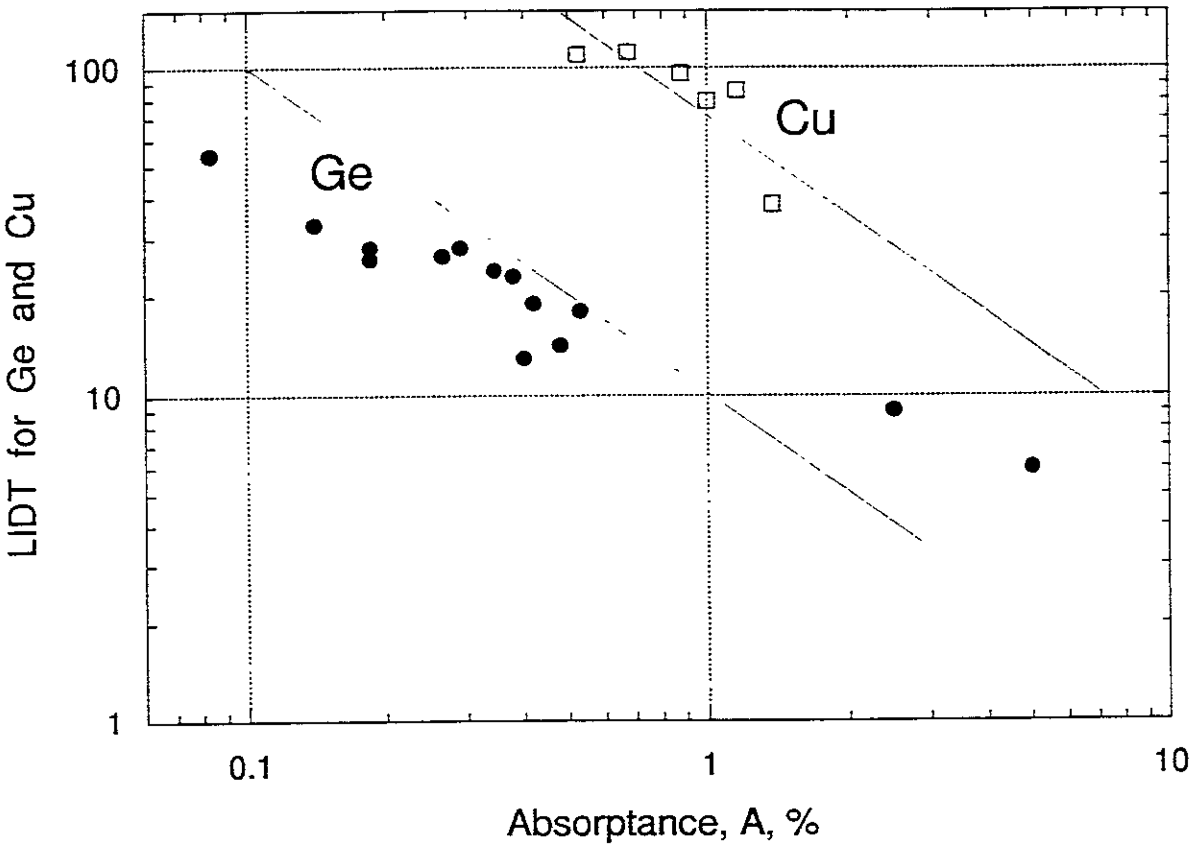

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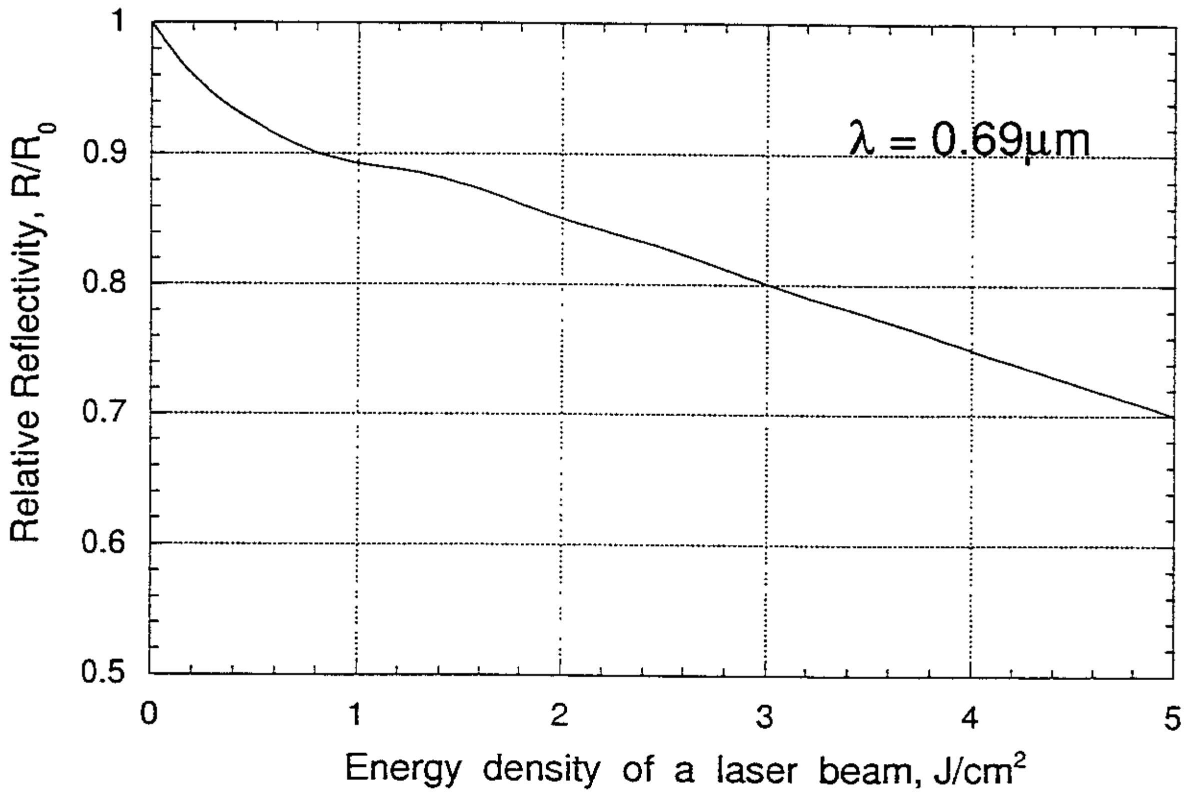
(a)



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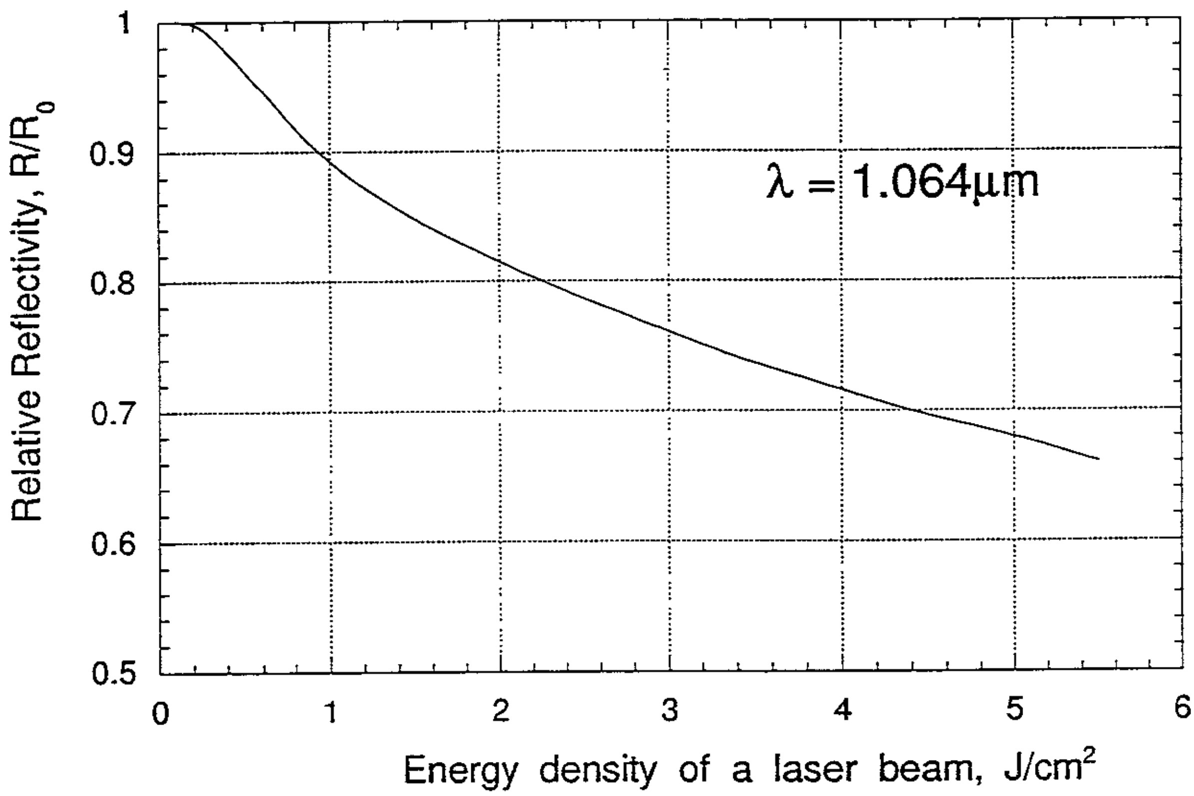
(b)



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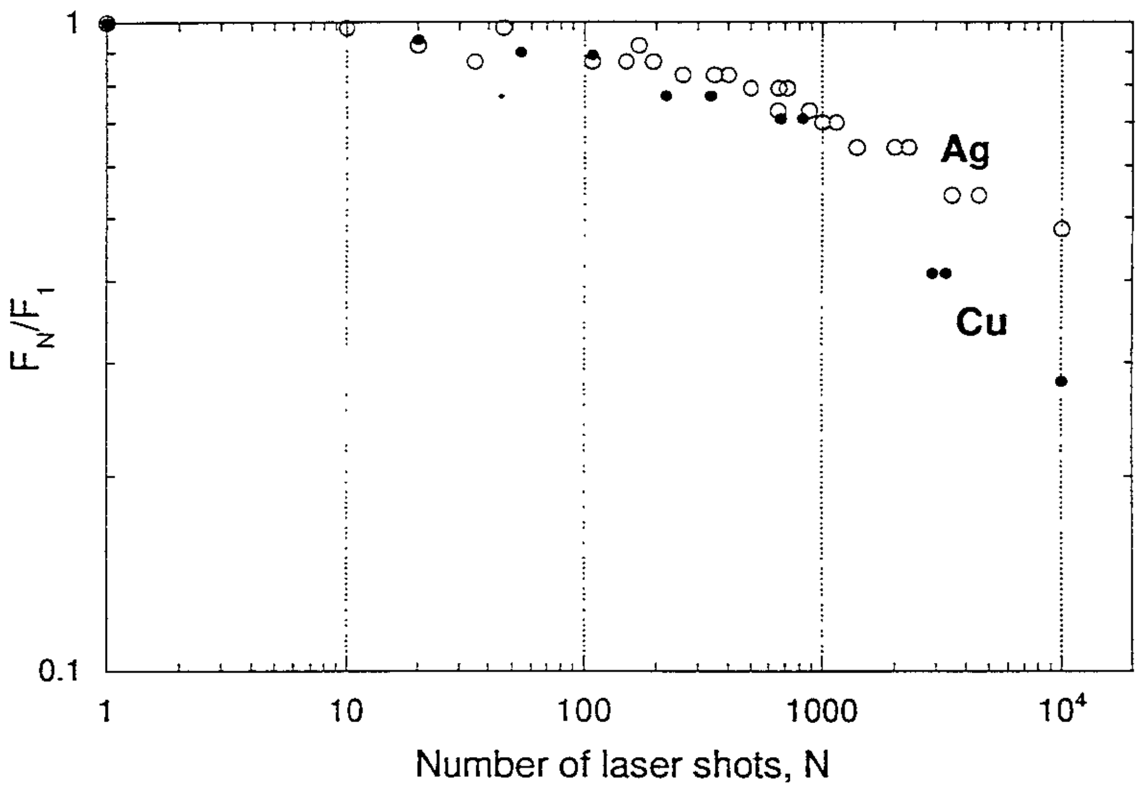

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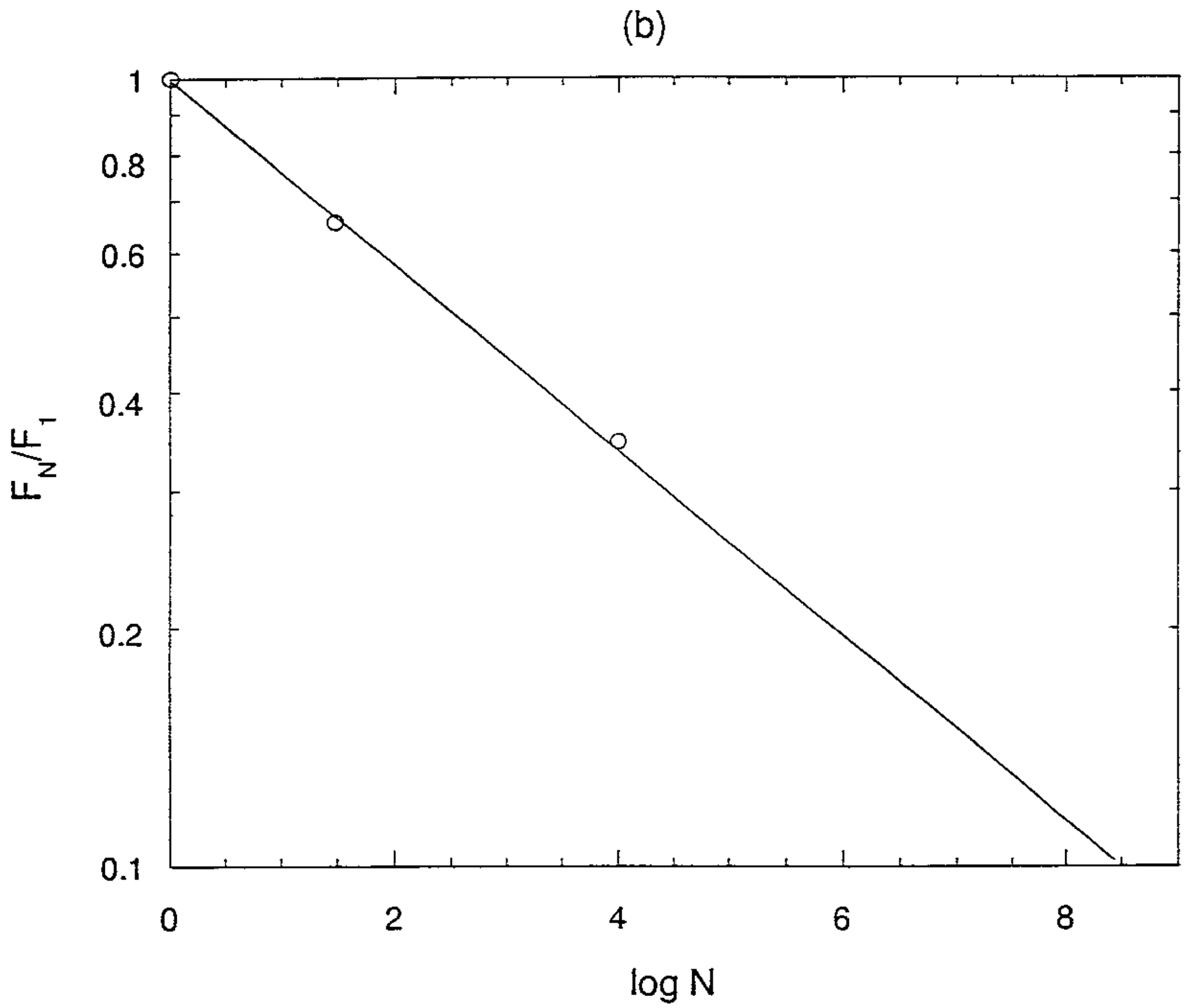
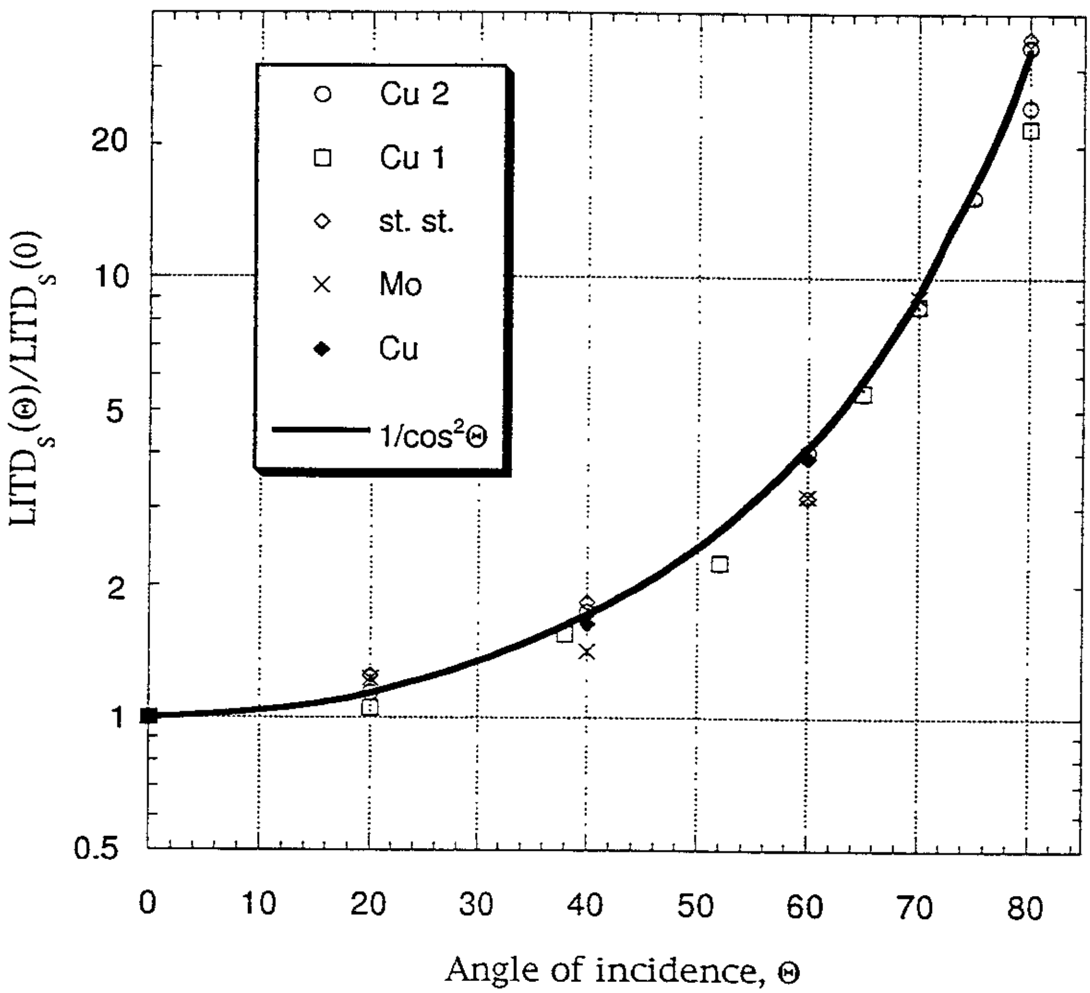


Fig. 4. (b) Change of LIDT values with increasing number of laser shots Mo [8].



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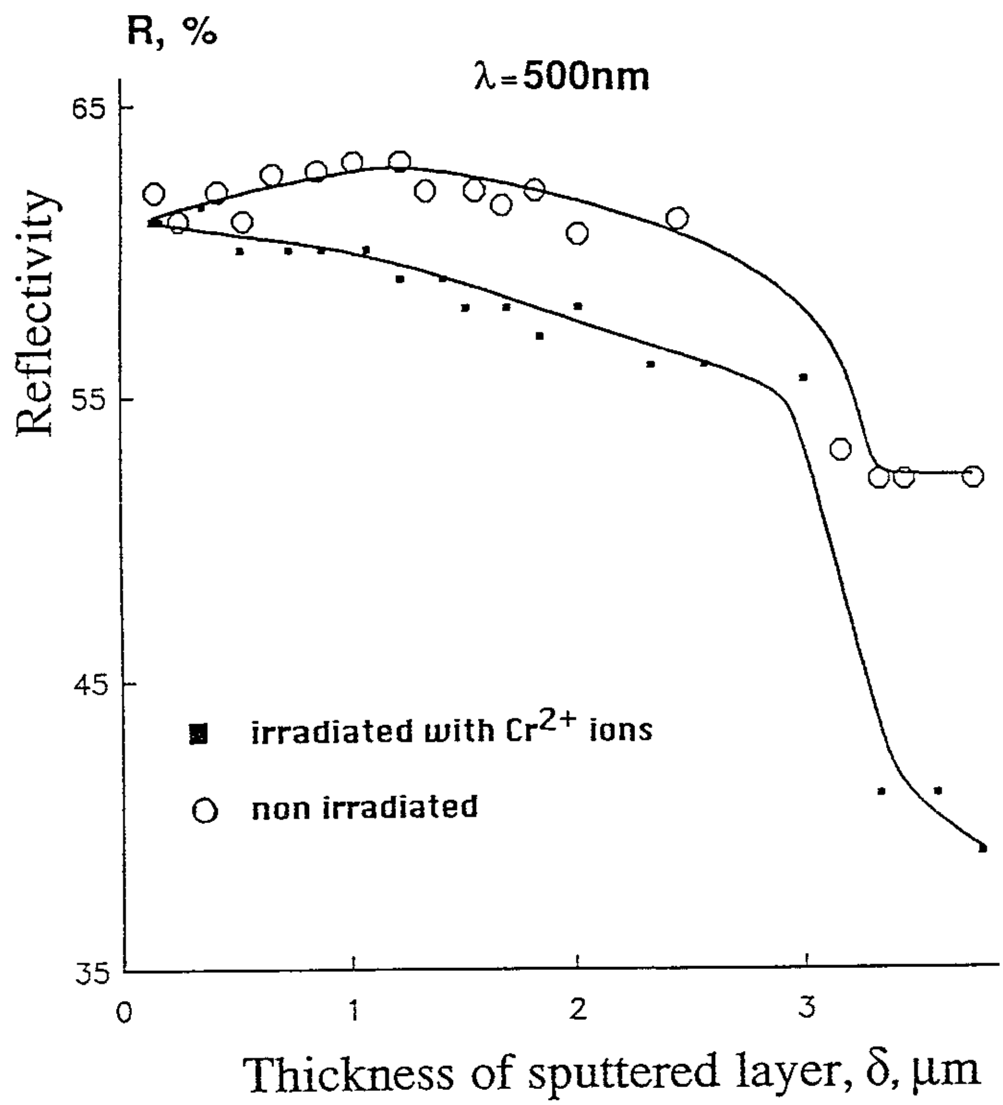

Fig. 6. (a) Dependence of reflectivity of stainless steel on the thickness of layer sputtered by ions of deuterium plasma.

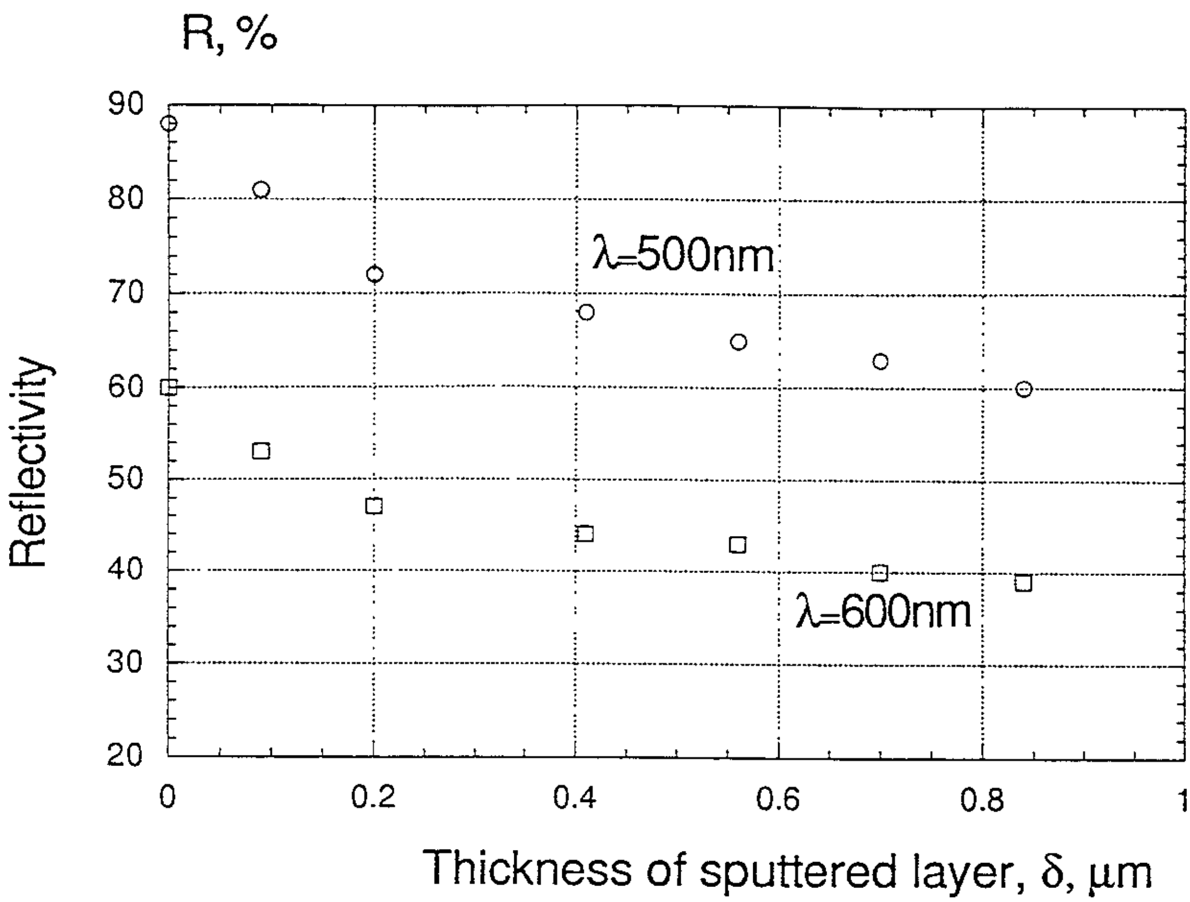

Fig. 6. (b) Dependence of reflectivity of copper mirrors on the thickness of layer sputtered by ions of deuterium plasma.

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