

PACS numbers: 07.85.Jy, 61.05.cf, 61.05.cm, 61.80.-x, 68.37.Lp, 68.65.Ac, 81.15.Jj

« », 21, 61002

$\Phi \leq 1,3 \cdot 10^{18}$  /  $\text{cm}^2$ ) (  $\text{He}^+$   $\Phi \leq 5 \cdot 10^{20}$  /  $\text{cm}^2$   $\text{Ar}^+$  )  
 Mo-Si Si-Mo MoSi<sub>8,2</sub> MoSi<sub>3,9</sub> He<sup>+</sup> Ar<sup>+</sup>  
 Mo/Si, He<sup>+</sup>,  
 (T ≤ 260°C), 2 — (T > 260°C) : 1 —  
 Q<sub>1</sub> ≈ 0,02 Q<sub>2</sub> ≈ 0,5  
 Ar<sup>+</sup>  $\Phi \leq 1,3 \cdot 10^{18}$  /  $\text{cm}^2$ ) (  $\text{He}^+$   $\Phi \leq 5 \cdot 10^{20}$  /  $\text{cm}^2$  )  
 Mo-Si Si-Mo MoSi<sub>8,2</sub> MoSi<sub>3,9</sub> He<sup>+</sup> Ar<sup>+</sup>  
 Mo/Si, He<sup>+</sup>,  
 (T > 260°C) : 1 — (T ≤ 260°C), 2 —  
 Q<sub>1</sub> ≈ 0,02 Q<sub>2</sub> ≈ 0,5

Thickness of silicide phases at Mo-on-Si and Si-on- interfaces increases identically and linearly with a dose of irradiation at the small doses (by He<sup>+</sup>

ions to  $\Phi \leq 5 \cdot 10^{20}$  ion/m<sup>2</sup> and Ar<sup>+</sup> ions to  $\Phi \leq 1.3 \cdot 10^{18}$  ion/m<sup>2</sup>). Mean atomic composition of amorphous intermixed zones corresponds to alloys of MoSi<sub>8,2</sub> and MoSi<sub>3,9</sub> compositions under the irradiation by He<sup>+</sup> and Ar<sup>+</sup> ions, respectively. Density of the amorphous intermixed areas decreases when the irradiation dose increases. There are two areas corresponding to weak dependence ( $T_{irr} \leq 260^\circ\text{C}$ ) and strong dependence ( $T_{irr} > 260^\circ\text{C}$ ) of ion-beam mixing of Mo/Si multilayered structures irradiated by He<sup>+</sup> on irradiation temperature. Activation energies of the ion-beam mixing are equal  $Q_1 \approx 0.02$  eV  $Q_2 \approx 0.5$  eV for the indicated areas, respectively. The features of the ion-beam mixing are explained by mixing in collision subcascades.

( 25 2010 . )

1.

?

10 ,

?

2.

$E_d'$  ( ) , ( )

( ) . . .

[1-3].

[1].

( ) ,

[4, 5].

SRIM2003 [6].

[7, 8].

**1.**

<i>I.</i>			
1.	( $\cong 10^{-13}$ )	-	-
2.	( $\cong 10^{-12}$ )	-	-
<i>II.</i>			
1.	( $\cong 10^{-12}$ )	-	-
2.		-	-
<i>III.</i>			
1.		-	-
2.		-	-
<i>IV.</i>			

( . 1) [7].

1.

(long-range mixing).

2.

( . . 1).

( . . . ),

[8].

(f)

(Φ)  
(F<sub>d</sub>):

$$f \propto (\Phi F_d)^{1/2}. \tag{1}$$

$$h \propto (\tilde{D}t)^{1/2}, \tag{2}$$

h — ,  $\tilde{D}$  —

[9-11]:

$$D_{\text{cas}} t = 0,067 (F_d \langle r^2 \rangle \Phi) / (N_0 E_d), \quad (3)$$

$$D_{\text{cas}} \text{ — } \quad , \langle r^2 \rangle \text{ — } \\ E_d \text{ — } \quad , \Phi \text{ — } \quad , N_0 \text{ — } ,$$

$(\Delta H_{\text{mix}})$  [12]:

$$Dt/\Phi = (D_{\text{cas}} t/\Phi)(1 - 2\Delta H_{\text{mix}}/kT), \quad (4)$$

$$D_{\text{cas}} t \text{ — } \quad , \quad (3), \dots \\ \Delta H_{\text{mix}} = 0.$$

$$(Pt-Pd, Hf-Zr, W-Mo, Ta-Nb, Au-Ag), \\ (D_{\text{cas}} t/\Phi) \\ (3).$$

[13]

$$Pt-Pd. \quad Au-Ag \quad ,$$

[8]

$D \cong 10^{-4} \text{ cm}^2/\text{s}$ ,  $(D \cong 10^{-8} \text{ cm}^2/\text{s})$

$(F_d)$ ,  
 (3).

$\Phi \frac{(D_{\text{cas}t})/(\Phi F_d)}{F_d}$ .

$(D_{\text{cas}t})/(\Phi F_d)$

[14] Pt - Pd  
 (Ne),  
 $(D_{\text{cas}t})/(\Phi F_d)$   
 (3) (Ar<sup>+</sup>)  
 $(D_{\text{cas}t})/(\Phi F_d)$   
 (3).  
 $F_d$  ( )  
 ( )  $F_d$

(3)

0°

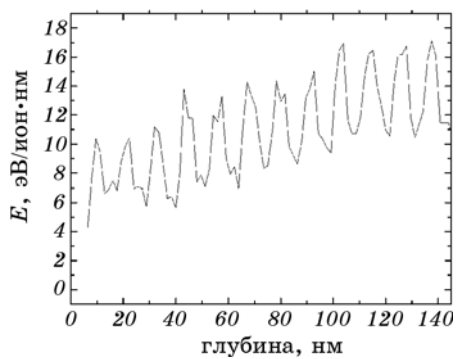
$100^\circ$   
 $0,6T$  ,  
 ( ) .  
 0,1-0,3 [8].  
 (  $Q_v^m$  )  
 ( ) Mo-Si,  $Ar^+$  200  
 390-630  $Q_{ion}^{mix} = 0,3$  ( $Q_{ion}^{mix} = 0,03$  630-790 ) [15].  
 18]. [16-  
 Mo-Si  
 [18].  
 ( ) ,  
 $10^{-11}$  .

3.

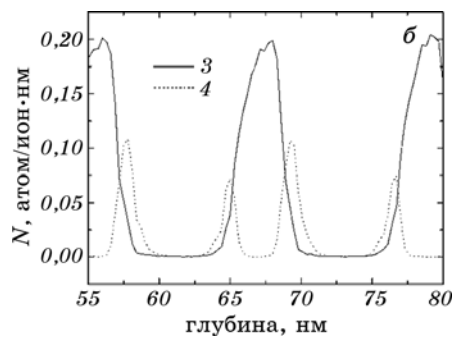
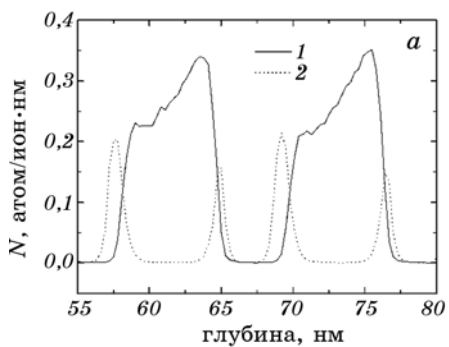
$n = 12$  Mo/Si  $H = 11,3$   
 $\approx 0,4$  [19]  
 $He^+$  40 Mo/Si  
 [20].



Mo/Si  $\text{Ar}^+$  « 175 -1 » 1-5 /  $^2$ . 2 .  
 . . ( . ). .  
 - Mo/Si SRIM 2003 [6].  
 .  
 $\text{CuK}_{\alpha_1}$  .  
 3 . (220) ,  
 .  
 [21, 22].  
 ( ) .  
 (SEMI, . )  $\times 270000-420000$   
 100 . ,  
 . ,  
 .  
 4.  
 4.1. Mo/Si  
 $3 \cdot 10^{19}-5 \cdot 10^{20}$   $\text{He}^+$  40  
 - [11]  
 . ( , , ) ,



1.  $He^+$ , Mo/Si, 40  
 Mo/Si,  $He^+$   
 [23-31].  $He^+$   
 Si.  $He^+$  1.  
 2 Si Mo



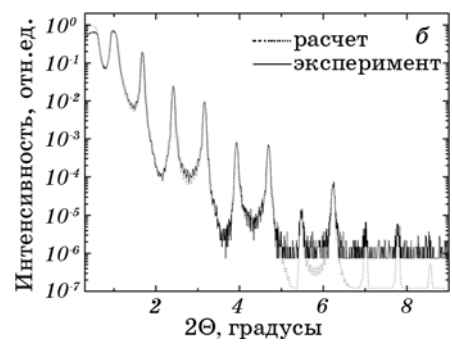
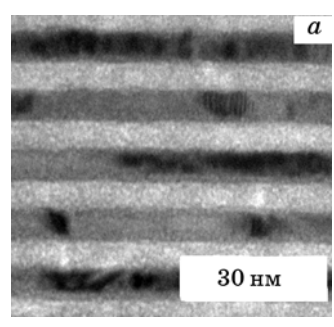
2. ( ) Mo/Si: 1 — ( )  
 Si; 2 — ; 3 —  
 ; 4 —

$$E_{d(\text{Mo})}(\text{Mo}) = 45, E_{d(\text{Si})}(\text{Si}) = 13, E_{d(\text{Mo})}(\text{MoSi}_2) = E_{d(\text{Si})}(\text{MoSi}_2) = 18$$

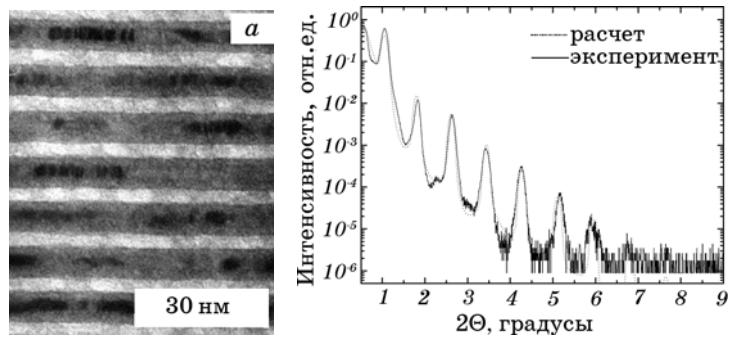
$$h_{\text{Si-Mo}} \approx 0,6 \quad \text{Mo-Si} \quad h_{\text{Mo-Si}} \approx 1,1 \quad \text{Si-Mo}$$

(.4, ).

[25].

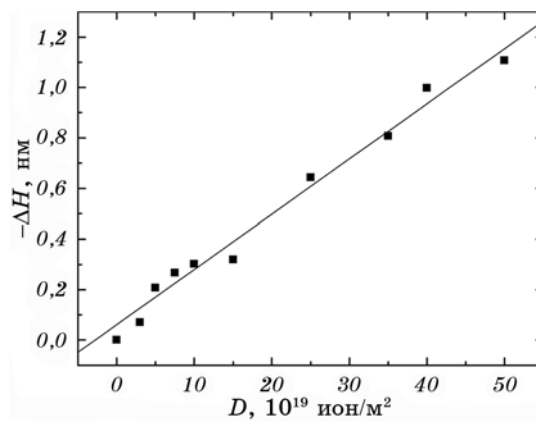


.3. ( ); Mo/Si ( ).



4. -  $4 \cdot 10^{20}$  /  $\text{м}^2$  ( ); Mo/Si ( ).

,  
 $\Phi \geq 1,5 \cdot 10^{20}$  /  $\text{м}^2$ .  $\Phi = 5 \cdot 10^{20}$   
 ( . 5).



5. Mo/Si

. 6.

[32–35].

1.

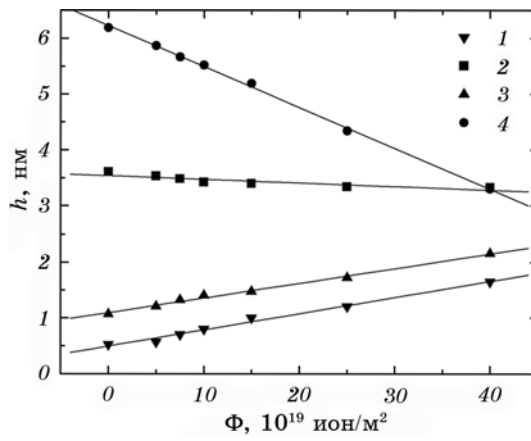
2.

Mo-Si Si-Mo.

3.

$(\Delta h_{Mo})$

$(\Delta h_{Si})$ ,



. 6.

Si.

Si-Mo; 2 — Mo/Si ; 3 — Mo-Si; 4 —

$(n/m)$   $Mo_mSi_n$  :

$$\Delta h_{Si} \rho_{Si} M_{Mo} / \Delta h_{Mo} \rho_{Mo} M_{Si} = n/m. \quad (5)$$

$$\Delta h_{Si} = 2,89 \quad , \quad \Phi = 4 \cdot 10^{20} / \text{cm}^2 \quad , \quad \Delta h_{Mo} = 0,275$$

( . 6).  $Mo_mSi_n$   $n/m = 8,2$ .

Mo-Si,  $n/m = 2$ .

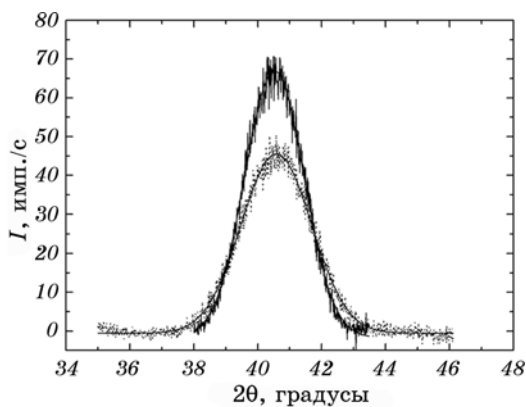
$MoSi_2$ ,  $Mo/Si_2$

1400°  $0,985\%$  Mo/Si

[32-35].  
Mo/Si

(110) Mo  
 $\Delta(2\theta) = 0,06^\circ$  ( . 7).

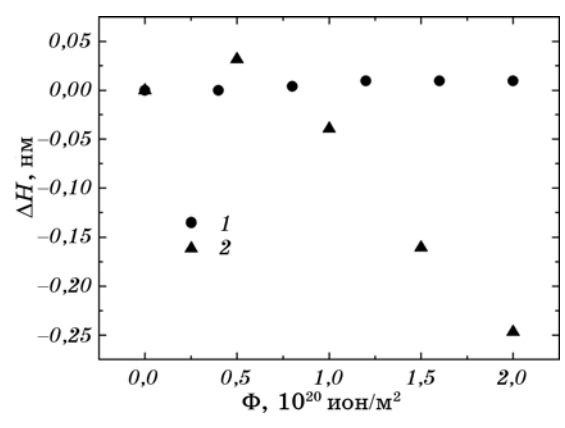
$d_{(110)}$  He<sup>+</sup> [36].



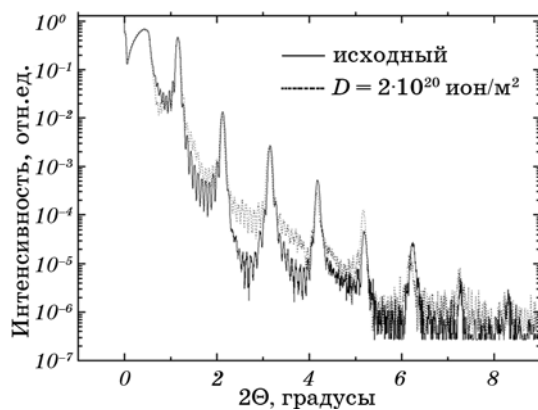
. 7. (110)Mo He<sup>+</sup> Mo/Si (  $\Phi = 3 \cdot 10^{20}$  )

[1, 2],  
 ( ),  
 ( ),  
 Mo/Si  
 Mo/Si, MoSi<sub>2</sub>/Si  
 ( ),  
 He<sup>+</sup> E = 40  
 MoSi<sub>2</sub>/Si Mo/Si  
 MoSi<sub>2</sub>/Si Mo/Si  
 [25, 26]  
 MoSi<sub>2</sub>/Si  
 H = 8,53  
 β = h<sub>MoSi<sub>2</sub></sub>/H = 0,42.

= 2 · 10<sup>20</sup> / 2



8. MoSi<sub>2</sub>/Mo/MoSi<sub>2</sub>/Si (2) He<sup>+</sup> MoSi<sub>2</sub>/Si (1) E = 40



( . 9. ) ( ) MoSi<sub>2</sub>/Si .

( . 9).

( , )

, . 9, -

He<sup>+</sup> , MoSi<sub>2</sub>/Si , -

MoSi<sub>2</sub>/Si - .

MoSi<sub>2</sub>/Mo/MoSi<sub>2</sub>/Si,  
3,98/3,88/3,85/6,44 .

MoSi<sub>2</sub>

. 8. -

D = 1·10<sup>20</sup> / <sup>2</sup> . , -

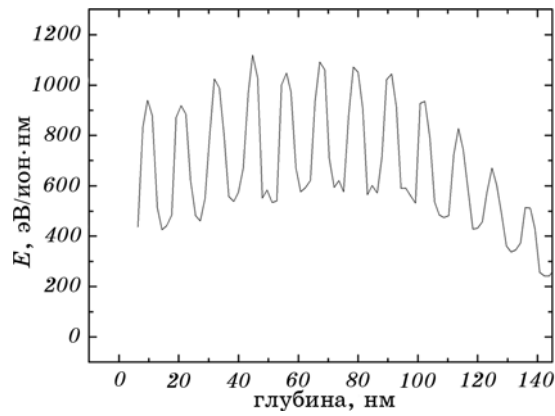
), ( -



4.2.

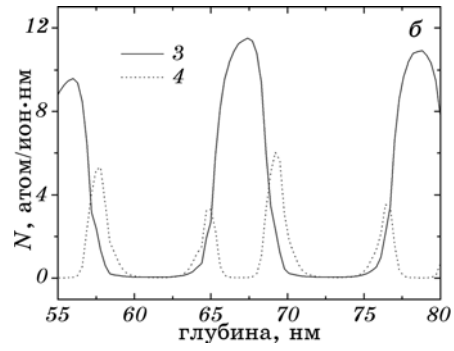
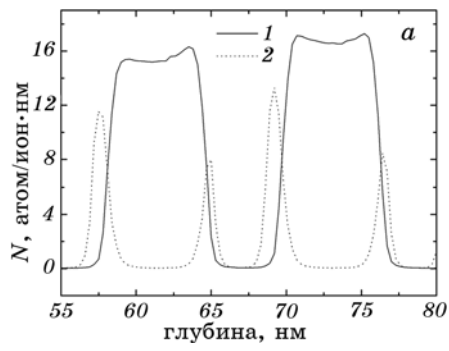
Mo/Si

Ar<sup>+</sup>, Mo/Si, [37].  
 Ar<sup>+</sup>, Mo/Si, Ar<sup>+</sup>.  
 . 10.  
 Si Mo 11  
 Mo/Si . 12.  
 $\leq 1,3 \cdot 10^{18}$   
 $/^2$   
 $1,3 \cdot 10^{18} /^2$  ( . 12, ).  
 Si . 2.  $1,3 \cdot 10^{18} /^2$   
 Mo-Si Si-Mo 0,8  
 0,4

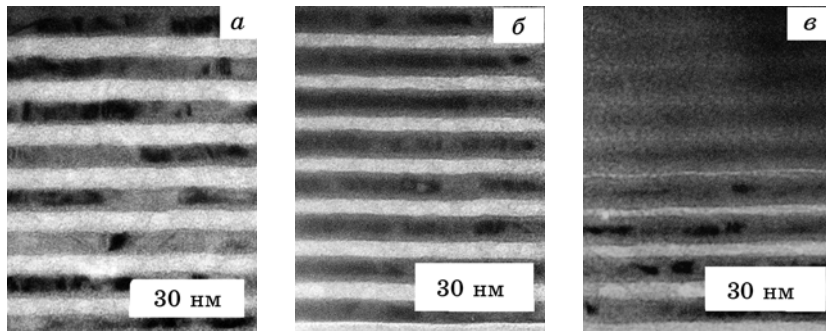


. 10.

Ar<sup>+</sup>, 175  
 Mo/Si.



.11. ( )  
 Ar<sup>+</sup> 175 : 1 — Mo/Si Si; 2 —  
 4 — ; 3 — ;  
 $1,3 \cdot 10^{18} / \text{cm}^2$  -  
 0,4 , 4  
 $6 \cdot 10^{18} / \text{cm}^2$  -  
 $12, 6 \cdot 10^{18} / \text{cm}^2$  -  
 ( . 10),  
 Ar<sup>+</sup>



.12. - ( )  $\Phi = 1,3 \cdot 10^{18} / \text{cm}^2$  Mo/Si  $\Phi = 6 \cdot 10^{18} / \text{cm}^2$   $\Phi =$

2. Ar<sup>+</sup>

Mo/Si, - .

	, / <sup>2</sup>	h <sub>Mo</sub> ,	h <sub>Si</sub> ,	h <sub>Mo-Si</sub> ,	h <sub>Si-Mo</sub> ,
5	0	3,7	5,6	1,4	0,8
5	5·10 <sup>17</sup>	3,6	4,6	1,8	1,2
5	1,3·10 <sup>18</sup>	3,3	3,6	2,2	1,6

Si.

4-

Mo/Si 4-

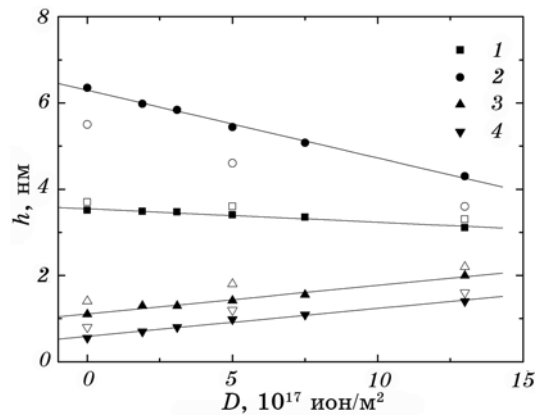
(ρ), (Δ)), (σ), (h), ( )

( . 2). ( )

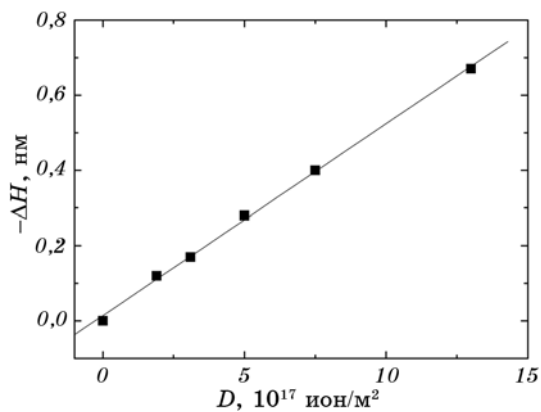
).

(Δ) 3. (h) (ρ) Ar<sup>+</sup>, (σ), ( )

·	/ <sup>2</sup>	Si			Mo- -Si			Si- -Mo			Δ ,				
		h,	ρ, / <sup>3</sup> σ,	h,	h,	ρ, / <sup>3</sup> σ,	h,	h,	ρ, / <sup>3</sup> σ,	h,		ρ, / <sup>3</sup> σ,			
1	0	3,51	10,0	0,42	6,42	2,33	0,32	1,1	5,9	0,54	0,55	5,9	0,40	11,58	-0,12
1	1,9·10 <sup>17</sup>	3,48	9,9	0,42	5,98	2,33	0,35	1,30	5,8	0,56	0,70	5,7	0,41	11,46	
2	0	3,51	10,0	0,43	6,41	2,33	0,30	1,10	5,9	0,55	0,56	5,7	0,42	11,58	-0,17
2	3,1·10 <sup>17</sup>	3,47	9,7	0,43	5,84	2,33	0,36	1,30	5,6	0,58	0,80	5,6	0,40	11,41	
3	0	3,50	10,0	0,44	6,31	2,33	0,32	1,10	6,0	0,56	0,61	5,8	0,39	11,52	-0,28
3	5·10 <sup>17</sup>	3,40	9,6	0,45	5,44	2,33	0,39	1,42	5,5	0,60	0,98	5,4	0,40	11,24	
4	0	3,52	10,0	0,44	6,30	2,33	0,30	1,10	5,9	0,52	0,56	5,8	0,39	11,46	-0,40
4	7,5·10 <sup>17</sup>	3,35	9,5	0,50	5,07	2,33	0,40	1,55	5,4	0,64	1,09	5,4	0,42	11,06	
5	0	3,51	10,0	0,40	6,27	2,33	0,32	1,10	6,0	0,48	0,60	5,9	0,39	11,48	-0,67
5	1,3·10 <sup>18</sup>	3,11	9,0	0,54	4,30	2,33	0,46	2,0	5,4	0,70	1,40	5,4	0,44	10,81	



. 13. (h) Mo/Si : 1  
 — ; 2 — Si; 3 — Mo-Si; 4 —  
 Si-Mo. — , —  
 .  
 (≅ 20 )  
 .  
 . 2 . 3 ,  
 -  
 -  
 . 13 , -  
 .  
 . 3. ,  
 -  
 ( . 2). ,  
 Mo/Si Ar<sup>+</sup> , -  
 (≅ 2 1,3·10<sup>18</sup> / <sup>2</sup>) -  
 , 0,4 .  
 Mo-Si Si-Mo  
 ≅ 0,8 . -  
 ( . 14). Mo/Si Ar<sup>+</sup> -  
 , He<sup>+</sup> -  
 -  
 :



. 14.

Mo/Si

Ar<sup>+</sup>.

Mo, , Mo-Si Si-  
 / <sup>2</sup> . . 2 , . 3, = 1,3 · 10<sup>18</sup>  
 (5), Δh<sub>Si</sub>/Δh<sub>Mo</sub> ≈ 5, n/m = 3,9  
 Ar<sup>+</sup> Mo<sub>m</sub>Si<sub>n</sub>. ,  
 MoSi<sub>2</sub>, ,  
 MoSi<sub>3,9</sub>. ,  
 , 6 · 10<sup>18</sup> / <sup>2</sup> ( . 12, ),  
 Δh<sub>Si</sub>/Δh<sub>Mo</sub> 5 3 4 ,  
 ,  
 (Ar, Kr, Xe ).  
 [8]  
 , 1 · 10<sup>19</sup> / <sup>2</sup> , . . ,  
 ( , ) ,

Mo/Si He<sup>+</sup>

4.3. He<sup>+</sup>

T = 275°C [38].

Mo/Si,

15

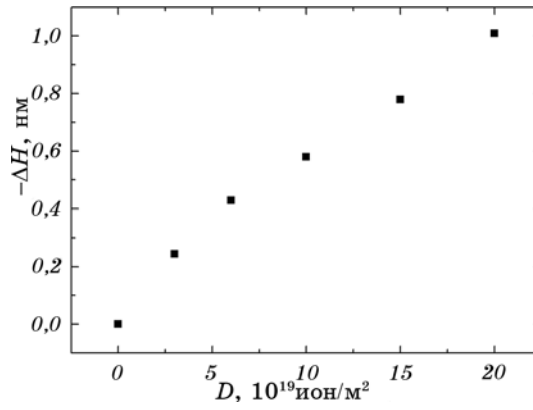
He<sup>+</sup> Ar<sup>+</sup>

(. 5 14),  
Mo/Si

(. 16).

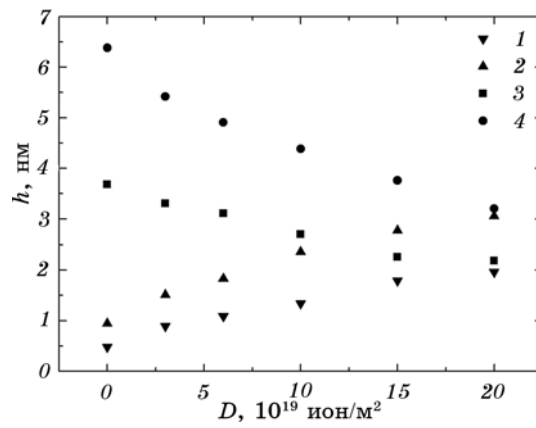
. 16

$$\rho = 6 / \text{Å}^3,$$



. 15.

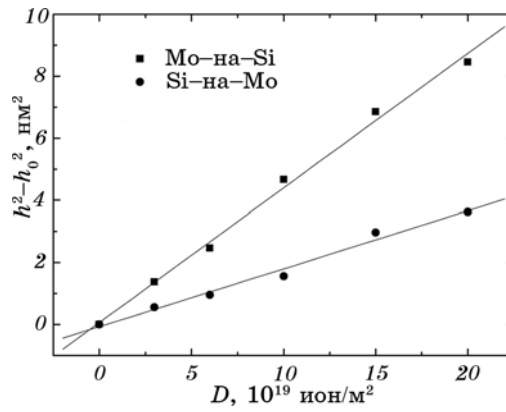
Mo/Si,



16. (h) Mo/Si, Si-Mo; 2 — Mo-Si; 3 — Si; 4 — MoSi<sub>2</sub>. T = 275°C: 1 —

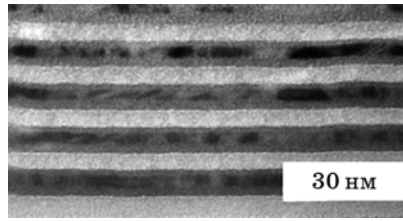
(. 17) [38].

(. 18). h<sub>Si-Mo</sub> ≈ 1,3 h<sub>Mo-Si</sub> ≈ 2



17. (h<sup>2</sup>)





18.  $\Phi = 7,5 \cdot 10^{19} / \text{cm}^2$

Mo/Si,  $T = 275^\circ\text{C}$ .

Mo-Si  
Si-Mo.  
(. 16 17).

$= 2 \cdot 10^{20} / 2,55$

$\Delta h_{\text{Si}} / \Delta h_{\text{Mo}} = 2,2 / \text{cm}^2$  (. 16).

$\Phi =$

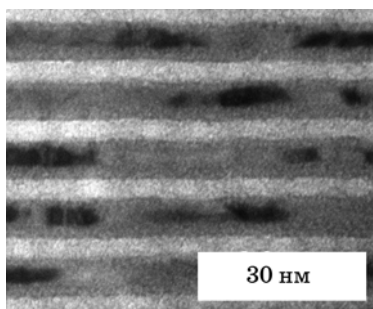


$\rho = 6 / \text{cm}^3$ .

Mo/Si

$T = 350^\circ\text{C}$  (. 19),

$(\Phi = 7,5 \cdot 10^{19} / \text{cm}^2)$



. 19.  $\Phi = 7,5 \cdot 10^{19} / \text{cm}^2$

Mo/Si,  $T = 350^\circ\text{C}$ .

$h_{\text{Mo-Si}} \approx 2,7$   
Si-Mo

$h_{\text{Si-Mo}} \approx 1,8$

Mo-Si

$/ \text{cm}^2$

$\Delta h_{\text{Mo-Si}} / \Delta h_{\text{Si-Mo}}$

$T = 275^\circ\text{C}$   $T = 350^\circ\text{C}$   $\Phi = 7,5 \cdot 10^{19}$

1,3.

Mo/Si,

$\Phi = 7,5 \cdot 10^{19} / \text{cm}^2$ ,

. 20 [38].

: 1)

( $T \leq 260^\circ\text{C}$ ) 2)

( $T > 260^\circ\text{C}$ ). [8]

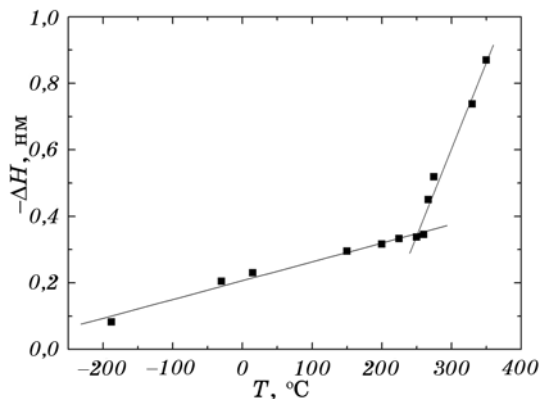
( $T = 360^\circ\text{C}$ )

Mo/Si.

$\ln(\Delta H^2)$

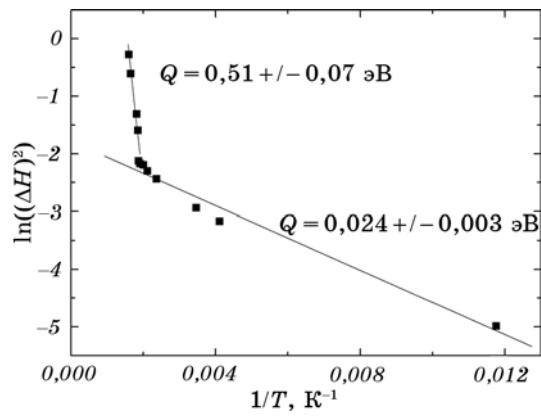
. 21.

$Q_1 \approx 0,02$



. 20.

Mo/Si.



21.  
Mo/Si.

$Q_2 \approx 0,5$

$Q_1 = 0,03$

[8]

$Q_2 = 0,3$

(2)

Si

4

MoSi<sub>2</sub>

5.

Mo/Si

Mo/Si

( $T \leq 260^\circ\text{C}$ )

. . .

He<sup>+</sup>, Ar<sup>+</sup>.

MoSi<sub>2</sub>, MoSi<sub>8,2</sub>, MoSi<sub>3,9</sub>.

(0,985% . Si)

[8]. [39],

Mo- -Si Si- -Mo,

$$f = (\Delta h)^2 / \Phi E \quad (6)$$

$\Delta h$  — ,  $\Phi$  —  $E$  —

,  $\Phi$  ,  $E$

$\text{He}^+ \quad 4 \cdot 10^{20}$   
 $E = 10,87$   
 $\Delta h = 1,09$   
 $f = 2,7 \cdot 10^{-4} \quad 5/$   
 $1,3 \cdot 10^{18} \quad / \quad 2$   
 $\Delta h = 0,9$   
 $E = 651$   
 $f = 9,6 \cdot 10^{-4} \quad 5/$   
 $\text{Ar}^+$   
 $\text{He}^+$   
 $\text{He}^+$   
 $\text{Mo-Si}$   
 $\text{Ar}^+$   
 $\text{Mo-Si}$   
 $\text{Ar}^+$   
 $[\text{5}, \text{8}]$   
 $(10^{-11})$   
 $(10^{-14} - 10^{-13})$   
 $t_{\text{cas}}$   
 $\text{He}^+ \quad \text{MoSi}_2/\text{Si} \quad 2 \cdot 10^{20} \quad / \quad 2$

MoSi<sub>2</sub>/Mo/MoSi<sub>2</sub>/Si

$$h_{\text{MoSi}_2} \approx 4$$

Si MoSi<sub>2</sub>,

1) Mo/Si, He<sup>+</sup>,  
 (T > 260°C) (T ≤ 260°C), 2)

$$\approx 0,5 \quad Q_1 \approx 0,02 \quad Q_2 \approx 0.5 \quad Q_2 \approx$$

$$( \quad ) \quad Q \approx 0,45Q, \quad Q -$$

[8].

( \quad )

Si-Mo. Mo-Si

6.

He<sup>+</sup> Ar<sup>+</sup>

Mo/Si

$$\text{Ar}^+ \quad \Phi \leq 1,3 \cdot 10^{18} \quad / \quad \text{He}^+ \quad \Phi \leq 5 \cdot 10^{20} \quad / \quad ^2,$$

Mo-Si Si-Mo

$f = 2,7 \cdot 10^{-4}$   $^{5/}$  ,  $Ar^+ - f = 9,6 \cdot 10^{-4}$   $^{5/}$   $He^+$

$MoSi_{8,2}$   $MoSi_{3,9}$   $He^+$   $Ar^+$

$(Ar^+ \Phi = 6 \cdot 10^{18} / ^2 MoSi_2)$

$Si_2/Si$   $Mo-$   $He^+$

$\Phi \leq 2 \cdot 10^{20} / ^2$   $h_{MoSi_2} \approx 4$

$MoSi_2/Mo/MoSi_2/Si,$

$\Phi \geq 1 \cdot 10^{20} / ^2$

$Mo/Si,$   $He^+,$   $: 1)$

$(T \leq 260^\circ C), 2)$   $(T >$

$> 260^\circ C)$

$Q_1 \approx 0,02$   $Q_2 \approx 0,5$

$Mo/Si,$

$Si-Mo.$   $Mo-Si$

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