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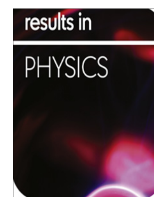

Kinetics of growth of thin-films of Co_2Si, Ni_2Si, WSi_2 and VSi_2 during a reactive diffusion process

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ABSTRACT

A theoretical approach is developed which describes the growth kinetics of thin films of near noble metal silicide (especially of cobalt silicide (Co_2Si) and nickel silicide (Ni_2Si)) and refractory metal silicide (particularly of tungsten disilicide (WSi_2) and vanadium disilicide (VSi_2)) at the interfaces of *metal–silicon* system. In this approach, metal species are presented as *A*-atoms, silicon as *B*-atoms, and silicide as *AB*-compound. The *AB*-compound is formed as a result of chemical transformation between *A*- and *B*-atoms at the reaction interfaces *A*/*AB* and *AB*/*B*. The growth of *AB*-compound at the interfaces occurs in two stages. The first growth stage is reaction controlled stage which takes place at the interface with excess *A* or *B*-atoms and the second stage is diffusion limited stage which occurs at both interfaces. The critical thickness of *AB*-compound and the corresponding time is determined at the transition point between the two growth stages. The result that follows from this approach shows that the growth kinetics of any growing silicides depends on the number of kinds of dominant diffusing species in the silicide layer and also on their number densities at the reaction interface. This result shows a linear-parabolic growth kinetics for WSi_2, VSi_2, Co_2Si, and Ni_2Si and it is in good agreement with experiment.

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Introduction

The thin film of near noble and refractory metal silicides gained wide attention in solid state reaction because of their applicability as low resistance contacts, gate electrodes, and interconnect materials in integrated circuit technology [1–3].

A number of works in the literature report the formation and growth kinetics of these silicides [4–7]. Silicide formation can be explained from two approaches: diffusion approach (which is considered as the conventional approach) and physicochemical approach (alternative approach to the former). From diffusion approach silicides are formed as a result of intermixing of silicon with metal species after the diffusion of either silicon atoms into the metal layer or metal atoms into the silicon layer. This intermixing is initiated by heat treatment process. Diffusion approach usually leads to loss of reaction controlled stage [8] due to lack of consideration for chemical reaction between metal and silicon species.

Unlike diffusion approach, physicochemical approach incorporates two processes: diffusion and chemical reaction. It describes metal and silicon layers as two immiscible layers with interface (s) separating them. Chemical reaction takes place between silicon and metal atoms at the interface(s). The metal atoms or silicon atoms or both are brought to the interface(s) by means of diffusion. This approach creates room for the possibility of accounting for chemical reaction contributions to the silicide growth during reaction controlled stage.

It is shown that the growth kinetics of silicides of near noble metals (for example, palladium, platinum, and cobalt) obey parabolic law [4–6] and the dominant atomic species in the first silicide phase (such as Ni_2Si, Pt_2Si, and Co_2Si) are unanimously identified as metal [2,7]. Metal species are reported as dominant species because the silicide is a metal rich silicide. However, there are different viewpoints on dominant species in the Pd_2Si phase [9–13].

In refractory metal silicides (such as molybdenum disilicide ($MoSi_2$), titanium disilicide ($TiSi_2$), tungsten disilicide (WSi_2), and vanadium disilicide (VSi_2)) the dominant diffusing species is reported as silicon [2–7]. This is due to the richness of this silicide phase in silicon. There are different growth kinetics exhibited by silicide in this phase [2,6–7]. For instance, in VSi_2 and WSi_2 growth kinetics are described as linear and parabolic, in $TiSi_2$ it's delineated as parabolic, and in $MoSi_2$ and $CrSi_2$ it is shown to be linear.

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In this paper, we present a model that describes the growth kinetics of the *AB*-compound layer based on the first approximation of reaction rate as product of reactant number densities. This approximation is in accord with mass action law. The speed of growth is proportional to reaction rate during the reaction controlled and diffusion limited stages. The *AB*-compound layer growth kinetics that follow from this approach show that the growth behavior of the growing layer can be explained from the viewpoint of the number of kinds of atomic species actively diffusing into the *AB*-layer during their formation process.

Model and result

Suppose that the *A*-layer occupies space $x < 0$ and the *B*-layer occupies space $x > 0$ in *A*–*B* system.

At time $t > 0$ heat treatment process commences in *A*- and *B*-layers. The interfaces *A*/*AB* and *AB*/*B* spatially separates *A*- and *B*-layers. *A*-atoms diffuse from the *A*-layer via *AB*-layer into interface *AB*/*B* and *B*-atoms diffuse from the *B*-layer via *AB*-layer into interface *A*/*AB*. At interface *AB*/*B*, diffuse *A*-atoms chemically react with surface *B*-atom to form *AB*-compound. Likewise, at interface *A*/*AB*, diffuse *B*-atoms interact chemically with surface *A*-atoms to form additional *AB*-compound. The *AB*-layer occupies space from $x = -h_a$ to $x = h_b$. The thickness of the compound layer formed at interface *A*/*AB* is denoted by $h_a(t)$ and at interface *AB*/*B* by $h_b(t)$. The total thickness of the *AB*-compound layer formed between *A*- and *B*-layers is designated by $h(t)$; $h(t) = h_a(t) + h_b(t)$ where h_a, h_b, and h are function of time t.

The rate of chemical transformation at interfaces of solid layers depends on number densities of *A* and *B* atoms. If there are excess *A*- or *B*-atoms at the interface, the rate of reaction remains the same with change of number density of *A*-or *B*-atoms [14]. On the other hand if number densities of *A*- and *B*-atoms are approximately equal ($\upsilon_a n_a \approx \upsilon_b n_b{}^0$ or $\upsilon_b n_b \approx \upsilon_a n_a{}^0$), then the rate of *AB*-compound formation can be represented in the first approximation as product of *A*- and *B*-atomic number densities. Where $n_a{}^0$ and $n_b{}^0$ are number densities of *A*- and *B*-atoms in *A*- and *B*-layers respectively, n_a and n_b are number densities of *A*- and *B*-atoms inside the *AB*-layer, υ_a and υ_b are stoichiometric coefficients of *A*- and *B*-atoms.

Thus the rate of chemical reaction between *A*- and *B*-atoms, at reaction interfaces *A*/*AB* and *AB*/*B* can be approximately expressed in two stages as follows:

$$R_a = \begin{cases} \gamma (n_a^0)^2 = const & \upsilon_b n_b(-h_a(t)) \geqslant \upsilon_a n_a^0 \\ \gamma n_a^0 n_b(-h_a(t)) & \upsilon_b n_b(-h_a(t)) \leqslant \upsilon_a n_a^0 \end{cases}$$
$$R_b = \begin{cases} \gamma (n_b^0)^2 = const & \upsilon_a n_a(h_b(t)) \geqslant \upsilon_b n_b^0 \\ \gamma n_b^0 n_a(h_b(t)) & \upsilon_a n_a(h_b(t)) \leqslant \upsilon_b n_b^0 \end{cases} \quad (1)$$

where $n_b(-h_a(t))$ and $n_a(h_b(t))$ are the number densities of *B*- and *A*-atoms which diffuse into reaction interfaces *A*/*AB* and *AB*/*B*, γ is the reaction rate constant, R_a and R_b are the reaction rates at interfaces *A*/*AB* and *AB*/*B*.

Due to this approximation, the growth of the *AB* layer can be described in two stages. The first growth stage occurs when there are excess of one kind of diffusing atoms, for example, excess *A*-atoms at interface *AB*/*B* or excess *B*-atoms at interface *A*/*AB* and the second growth stage takes place when there are no excesses of any kind of atoms at the corresponding interfaces.

The growth rate of the *AB*-layer is determined by both diffusion of *A*- and *B*-atoms inside the *AB*-layer and rate of reaction at interfaces:

$$\frac{dh}{dt} = \frac{dh_a}{dt} + \frac{dh_b}{dt} = V_{ab}\left(\gamma n_a^0 n_b(-h_a(t)) + \gamma (n_b^0)^2\right). \quad (2a)$$

Eq. (2a) holds only if *A*-atoms are in excess at interface *AB*/*B* or

$$\frac{dh}{dt} = \frac{dh_a}{dt} + \frac{dh_b}{dt} = V_{ab}\left(\gamma (n_a^0)^2 + \gamma n_b^0 n_a(h_b(t))\right). \quad (2b)$$

Eq. (2b) holds only if *B*-atoms are in excess at interface *A*/*AB*, where V_{ab} is the volume of one molecule of *AB*-compound.

Suppose that all *A*-atoms at *AB*/*B* interface and all *B*-atoms at *A*/*AB* interface reacted at once. Therefore the growth of the *AB*-compound layer is determined by flux of *A*-atom toward the *B*-layer and flux of *B*-atom toward the *A*-layer. Thus we consider the diffusion of *A*- and *B*-atoms inside the *AB*-compound layer.

Diffusion of *A*- and *B*-atoms inside the *AB*-layer is described by Fick's second law under a stationary condition thus:

$$D_{a(b)} \frac{\partial^2 n_{a(b)}(x)}{\partial x^2} = 0. \quad (3)$$

With corresponding boundary conditions:

$$J_a(h_b(t)) = -D_a \nabla n_a(x) = \upsilon_a \gamma n_b^0 n_a(h_b(t)); \quad J_b(-h_a(t)) = -D_b \nabla n_b(x) = \upsilon_b \gamma n_a^0 n_b(-h_a(t));$$

$$n_a(-h_a(t)) = n_a^0; \quad n_b(h_b(t)) = n_b^0.$$

where J_a and J_b are fluxes of *A*- and *B*-atoms, D_a and D_b are diffusivities of *A*- and *B*-atoms.

Solving Eq. (3) with boundary conditions for the first stage of layer growth (before critical time), we obtain an expression for the distribution of *A*- and *B*-atoms inside the *AB*-compound layer when *A*-atom is in excess at *AB*/*B* interface:

$$n_a(x) = -\frac{\gamma (n_b^0)^2}{D_a}(x + h_a) + n_a^0 \quad \text{and}$$
$$n_b(x,t) = \frac{\gamma n_a^0 n_b^0 \upsilon_b}{D_b + \gamma n_a^0 \upsilon_b h(t)}(x - h_b) + n_b^0 \quad (4a)$$

And for excess *B*-atoms at *A*/*AB* interface, the distribution of *A*- and *B*-atoms in the *AB*-layer is described by:

$$n_a(x,t) = \frac{\gamma n_a^0 n_b^0 \upsilon_a}{D_a + \gamma n_b^0 \upsilon_a h(t)}(x + h_a) + n_a^0 \quad \text{and}$$
$$n_b(x) = -\frac{\gamma (n_a^0)^2}{D_b}(x - h_b) + n_b^0. \quad (4b)$$

Number densities of *A*-atoms at interface *AB*/*B* and *B*-atoms at interface *A*/*AB* during the second growth stage are:

$$n_a(h_b(t)) = \frac{D_a n_a^0}{D_a + \gamma n_b^0 \upsilon_a h(t)} \quad \text{and}$$
$$n_b(-h_a(t)) = \frac{D_b n_b^0}{D_b + \gamma n_a^0 \upsilon_b h(t)}. \quad (5)$$

If there are excess *A*-atoms at reaction interface *AB*/*B* at time $\boldsymbol{t} < \boldsymbol{t_c}$, ($\boldsymbol{t_c}$, is the critical time), the *AB*-layer at this interface grows under reaction controlled process and at *A*/*AB* interface the growth is diffusion limited and vice versa for excess *B*-atoms at interface *A*/*AB*; therefore, the relationship between time and layer thickness can be found by solving either Eq. (2a) or (2b)

$$t = \frac{h(t)}{\gamma V_{ab}(n_b^0)^2} - \frac{D_b \upsilon_a^2}{\gamma^2 \upsilon_b^3 V_{ab}(n_b^0)^3} ln\left[\frac{\gamma n_a^0 n_b^0 \upsilon_b^2 h(t)}{D_b(n_a^0 \upsilon_a + n_b^0 \upsilon_b)} + 1\right] \quad (6a)$$

or

$$t = \frac{h(t)}{\gamma V_{ab}(n_a^0)^2} - \frac{D_a \upsilon_b^2}{\gamma^2 \upsilon_a^3 V_{ab}(n_a^0)^3} ln\left[\frac{\gamma n_a^0 n_b^0 \upsilon_a^2 h(t)}{D_a(n_a^0 \upsilon_a + n_b^0 \upsilon_b)} + 1\right]. \quad (6b)$$

Corresponding solutions to Eqs. (2a) and (2b) are expressed in Eqs. (6a) and (6b) respectively.

However, if there are no excess A- or B-atoms at the reaction interfaces no reaction controlled growth would occur at either AB/B or A/AB-interface and growth at both interfaces would be predominantly diffusion limited at all time.

$$\text{At critical time } t_c,\quad h(t)=h_c:\ \nu_a n_a(h_b(t_c))=\nu_b n_b^0 \quad \text{or} \quad \nu_b n_b(-h_a(t_c))=\nu_a n_a^0 \tag{7}$$

where $n_a(h_b(t_c))=\frac{D_a n_a^0}{D_a+\gamma n_b^0 \nu_a h_c}$ and $n_b(-h_a(t_c))=\frac{D_b n_b^0}{D_b+\gamma n_a^0 \nu_b h_c}$.

Critical thickness, h_c is obtained as follows:

$$h_c=\frac{D_a(n_a^0\nu_a-n_b^0\nu_b)}{\gamma\nu_a\nu_b(n_b^0)^2}. \tag{8a}$$

or

$$h_c=\frac{D_b(n_b^0\nu_b-n_a^0\nu_a)}{\gamma\nu_a\nu_b(n_a^0)^2}. \tag{8b}$$

Eq. (8a) holds at interface AB/B under reaction controlled process or Eq. (8b) at A/AB under the same process. It is worth noting that critical thickness cannot takes place at two interfaces at the same time. It can only occur at the interface that has excess atomic species.

For critical time, substitute $\boldsymbol{t=t_c}$, and $\boldsymbol{h=h_c}$ in Eq. (6a) or (6b)

$$t_c=\frac{h_c}{\gamma V_{ab}(n_b^0)^2}-\frac{D_b\nu_a^2}{\gamma^2\nu_b^3 V_{ab}(n_b^0)^3}In\left[\frac{\gamma n_a^0 n_b^0\nu_b^2 h_c}{D_b(n_a^0\nu_a+n_b^0\nu_b)}+1\right] \tag{9a}$$

or

$$t_c=\frac{h_c}{\gamma V_{ab}(n_a^0)^2}-\frac{D_a\nu_b^2}{\gamma^2\nu_b^3 V_{ab}(n_a^0)^3}In\left[\frac{\gamma n_a^0 n_b^0\nu_a^2 h_c}{D_a(n_a^0\nu_a+n_b^0\nu_b)}+1\right]. \tag{9b}$$

Eq. (9a) is the corresponding critical time of Eqs. (8a) and (9b) is the corresponding critical time of Eq. (8b).

The growth rate of the AB-compound layer after critical time (second stage of growth) is described by:

$$\frac{dh(t)}{dt}=\gamma V_{ab}\left(n_a^0 n_b(-h_a(t))+n_b^0 n_a(h_b(t))\right). \tag{10}$$

Substitute Eq. (5) into Eq. (10) and integrate the resulting equation; a connection between time and layer thickness is established:

$$t=t_c+\phi_1(h^2(t)-h_c^2)+\phi_2(h(t)-h_c)-\phi_3\ln\left[\frac{\phi_4 h(t)+\phi_5}{\phi_4 h_c+\phi_5}\right], \tag{11}$$

where

$$\phi_1=\left[2V_{ab}\left[D_b n_b^0+D_a n_a^0\right]\right]^{-1},$$

$$\phi_2=\left[(D_a n_a^0)^2+(D_b n_b^0)^2\right]\left[\gamma V_{ab} n_a^0 n_b^0\left[D_b n_b^0+D_a n_a^0\right]^2\right]^{-1},$$

$$\phi_3=D_a D_b\left[D_a n_a^0-D_b n_b^0\right]^2\left[\gamma^2 V_{ab} n_a^0 n_b^0\left[D_b n_b^0+D_a n_a^0\right]^3\right]^{-1},$$

$$\phi_4=\gamma\left[D_b n_b^0+D_a n_a^0\right],\quad \phi_5=D_a D_b.$$

The kinetics of the first stage of the growth of the AB-compound layer expressed in Eqs. (6a) and (6b) shows time as both partly linear and partly natural logarithmic functions of layer thickness and Eq. (11) depicts time as partly parabolic and partly natural logarithmic functions of thickness. The natural logarithmic function in Eqs. (6a), (6b) and (11) is attributed to the simultaneous diffusion of A and B-atomic species in the AB-compound layer.

It is important to mention that the layer growth kinetic would be linear under reaction controlled process and parabolic under diffusion limited process, if only one kind of atomic species diffuses into the AB-compound layer. If, for example, only A-atoms diffuse into the AB-layer when there are excess of A-atom at AB/B interface during the first stage of growth (reaction controlled growth).

Equation (6a) transforms to a linear equation when $D_b = 0$

$$h(t)=V_{ab}\gamma(n_b^0)^2 t \tag{12a}$$

And Eq. (11) reduces to parabolic equation

$$\gamma\nu_a n_b^0\left(h^2(t)-h_c^2\right)+2D_a(h(t)-h_c)-2\gamma V_{ab}D_a n_a^0 n_b^0(t-t_c)=0. \tag{12b}$$

Likewise if only B-atom diffuses into the AB-layer when there are excess of B-atoms at A/AB interface during the same stage of growth, Eq. (6b) also changes to linear equation when $D_a = 0$

$$h(t)=V_{ab}\gamma(n_a^0)^2 t \tag{13a}$$

And Eq. (11) reduces to parabolic equation

$$\gamma\nu_b n_a^0\left(h^2(t)-h_c^2\right)+2D_b(h(t)-h_c)-2\gamma V_{ab}D_b n_a^0 n_b^0(t-t_c)=0. \tag{13b}$$

However, if there are no excess A- or B-atoms at either AB/B or A/AB interface, the first growth stage would be absent. In other words there would be no reaction controlled process and linear growth would not take place. Thus only parabolic growth (diffusion limited growth) would be feasible. Eq. (14a) would hold if there are only A-atoms diffusing into the AB-layer and Eq. (14b) would also hold if there are only B-atoms diffusing into the AB-layer under the second stage of growth.

$$\gamma\nu_a n_b^0 h^2(t)+2D_a h(t)-2\gamma V_{ab}D_a n_a^0 n_b^0 t=0, \tag{14a}$$

$$\gamma\nu_b n_a^0 h^2(t)+2D_b h(t)-2\gamma V_{ab}D_b n_a^0 n_b^0 t=0. \tag{14b}$$

The growth kinetics of four silicides (WSi_2, VSi_2, Co_2Si, and Ni_2Si) are studied based on the result of this model. The experimental data are taken from the literature [15–18] to determine the inter-diffusion coefficients of silicide layers under conventional furnace annealing process. We assume that the diffusivity of dominant species is the same as that of inter-diffusion coefficient of the growing silicides (since only one kind of species diffuses into the silicide layer). The diffusing species in each silicide layer are shown in Table 1.

The results of inter-diffusion coefficients for four silicides are depicted in Table 2 and they are obtained from Arrhenius equation

Table 1
Useful information on growth kinetics of silicides considered in this study.

AB-compound layer	Diffusing species under annealing condition in AB-layer	Formation temperature (K) used in this work	Growth kinetics (from this study)	Growth kinetics (from experiment)
WSi_2	Si [2,7]	1033 [15]	Linear and parabolic	Linear and parabolic [2,7]
VSi_2	Si [2,7]	873 [16]	Linear and parabolic	Linear and parabolic [7]
Co_2Si	Co [2,7]	763 [17]	Linear and parabolic	Parabolic [2,6–7]
Ni_2Si	Ni [2,7]	573 [18–19]	Linear and parabolic	Linear and parabolic[18]

Table 2
Data used for silicide layer thickness estimation.

AB-compoundlayer	Inter-diffusion coefficient of *AB*-layer (10^{-17} m^2/s)	Reaction rate constant (10^{-38} m^4/s)	Volume of *AB*-compound per molecule (10^{-29} m^3)	Number density of *A*- and *B*-atoms in *A*- and *B*-layers (10^{28} atoms/m^3)
WSi_2	1.000 [15]	4.700	4.300	W (6.3), Si (5.0)
VSi_2	0.029 [16]	0.910	4.000	V (5.2), Si (5.0)
Co_2Si	3.000 [17]	1.200	5.000	Co (9.1), Si (5.0)
Ni_2Si	1.100 (estimated)	0.620	3.300	Ni (9.14), Si (5.0)

Table 3
Critical thickness and time of *AB*-layer.

AB-layer	h_c (10^{-9} m)	t_c (s)
WSi_2	0.990	0.124
VSi_2	0.280	0.285
Co_2Si	66.000	44.000
Ni_2Si	47.000	92.000

Table 4
Activation energy and pre-exponential factor.

AB-layer	E_a (eV)	D_0 (m^2/s)
WSi_2	3.4 [15]	0.40 (estimated)
VSi_2	2.9 [16]	0.016 (estimated)
Co_2Si	–	–
Ni_2Si	1.5 [18,19]	0.000167 [18,19]

described in Eq. (15) based on the data available on D_0 and E_a in Table 4 at formation temperatures shown in Table 1

$$D_{\rm int} = N_{a(b)}D_{a(b)} = N_{a(b)}D_0 \exp\left(\frac{-E_a}{K_B T}\right), \tag{15}$$

where D_{int} is the inter-diffusion coefficient of the *AB*-layer, $N_{a(b)}$ is the atomic fraction of *A*- or *B*-atoms (which is equal to unity in case of one kind of diffusing species) in the *AB*-layer, D_0 is the pre-exponential factor, E_a is the activation energy, K_B (8.617×10^{-5} eV) is the Boltzmann constant, and *T* is the absolute temperature.

The layer thickness of WSi_2 and VSi_2 is estimated with Eq. (13a) (for reaction controlled growth) and Eq. (13b) (for diffusion limited growth). The critical thickness between the two growth stages is obtained with Eq. (8b) and the corresponding critical time, t_c (when $D_a = 0$) is estimated with Eq. (9b). In a similar vein, the thickness of Co_2Si and Ni_2Si is obtained from Eq. (12a) (for reaction controlled growth) and Eq. (12b) (for diffusion limited growth). The critical thickness and time are estimated with Eqs. (8a) and (9a) respectively when $D_b = 0$. The results of critical thickness and time of the silicide layers are shown in Table 3. The results show that critical thickness is strongly dependent on the diffusivity of the active moving species in the silicide layer. The higher the diffusing rate of the active species the thicker the thickness becomes at the transition point.

The growth kinetics of four silicides considered in this study reveals a linear-parabolic relationship between layer thickness and time. The linear growth in both WSi_2 and VSi_2 layers is due to the reaction rate dependence on tungsten atomic density at W/WSi_2 interface and vanadium number density at V/VSi_2 interface during reaction controlled stage, while parabolic growth on the other hand is due to reaction rate dependence on both number densities of tungsten and silicon atoms at both interfaces in tungsten–silicon system. The same explanation applies to vanadium–silicon system. Linear growth in the Co_2Si layer occurs as a result of excess cobalt atoms at Co_2Si/Si interface during reaction controlled stage and parabolic growth arises in the Co_2Si layer due to the active diffusion of cobalt as the only moving atoms during diffusion limited stage in the Co_2Si layer. The same explanation holds for linear-parabolic growth in the Ni_2Si layer where nickel is the only active diffusing species.

Due to the small magnitude of layer thickness formed over a very short period of time during reaction controlled growth as shown in Table 3, the linear section of this curve is correspondingly

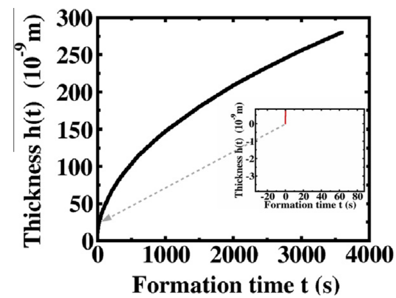

Fig. 1. The growth kinetics of tungsten disilicilde (WSi_2) at 1033 K. The dotted arrow shows the linear growth regime of WSi_2 under a reaction controlled process. The estimated time for the linear growth of WSi_2 is 0.124 s. The inserted graph shows the linear section of the curve.

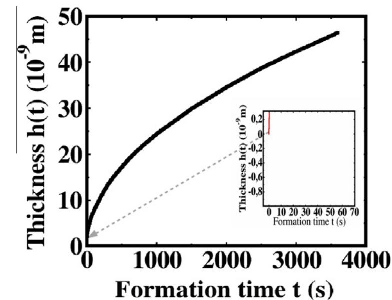

Fig. 2. The growth kinetics of vanadium disilicilde (VSi_2) at 873 K. The dotted arrow shows the linear growth region of VSi_2 over an estimated period of 0.285 s. The inserted graph also shows the linear section of the curve which appears parallel to the time axis due to short time involved during the growth process.

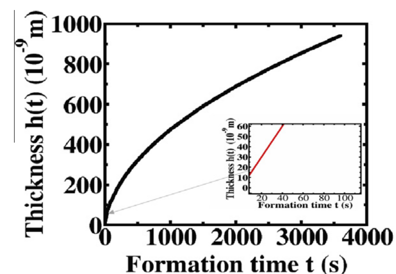

Fig. 3. The growth kinetics of cobalt silicilde (Co_2Si) at 763 K. The thin arrow shows the linear growth regime of Co_2Si over a period of 44 s. The inserted graph as well shows the linear section of the curve under a reaction controlled process.

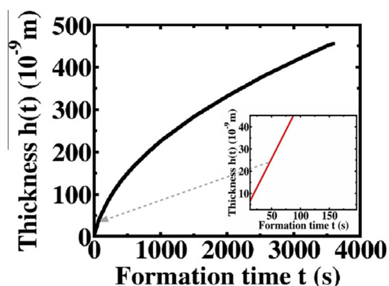

Fig. 4. The growth kinetics of nickel silicide (Ni_2Si) at 573 K. The dotted arrow indicates the linear growth of Ni_2Si over a period of 92 s under a reaction controlled process. The inserted graph also shows the linear section of the curve.

small that the growth kinetics appear to be predominantly parabolic in Figs. 1–4. The silicide growth is considered over a period of 3600 s in all the layers.

Conclusions

The theoretical approach presented here shows that the growth kinetics of any growing silicides can be described in terms of reaction rate between silicon and metal species at the reaction interfaces. This study shows that chemical reaction rate can either depend on silicon density or metal species density or both during the reactive diffusion process. This dependence determines the number of possible growth stages and also responsible for the correlation that arises between time and layer thickness during the growth stages. For example, reaction controlled growth occurs when the reaction rate depends on either silicon or metal species density and the relationship between time and layer thickness during this stage can either be linear or more complex than linear depending on the number of kinds of diffusing species in the silicide layer, however, in diffusion limited growth stage chemical reaction rate relies on both metal and silicon densities at the reaction interface and the link between time and thickness can either be parabolic or more complex than parabolic which also depends on the number of kinds of active moving species in the silicide growing layer.

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