Rapid thermal process by RF heating of nano-graphene layer/silicon substrate structure: Heat explosion theory approach

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Abstract. RF heating kinetics of a nano-graphene layer/silicon substrate structure is analyzed theoretically as a function of the thickness and sheet resistance of the graphene layer, the dimensions and thermal parameters of the structure, as well as of cooling conditions and of the amplitude and frequency of the applied RF magnetic field. It is shown that two regimes of the heating can be realized. The first one is characterized by heating of the structure up to a finite temperature determined by equilibrium between the dissipated loss power caused by induced eddy-currents and the heat transfer to environment. The second regime corresponds to a fast unlimited temperature increase (heat explosion). The criterions of realization of these regimes are presented in the analytical form. Using the criterions and literature data, it is shown the possibility of the heat explosion regime for a graphene layer/silicon substrate structure at RF heating.

1. Introduction
There is a number of investigations devoted to the induction heating of a conductor film/silicon substrate structure by a radio-frequency (RF) magnetic field perpendicular to the substrate surface [1-3]. The heat explosion theory [4] was used to describe the heating process. Results of the theory well agree with the experiments with Ti and Ta-Ti thin films (85-220 nm thickness) deposited on Si (111) and on Si (100) substrates [1-3]. Application of the RF heating allows one to prepare these structures with required properties. One drawback of using this technology is pollution of silicon substrates due to the fast diffusion of metallic impurities.

Here we propose a new rapid thermal process (RTP) which is based on RF heating of a nano-graphene layer deposited on the back side of a silicon substrate. The characteristic property of the method is that no additional heater is required, despite the fact that thickness of the graphene layer/Si substrate structure is less than a skin depth. In contrast to metals, the diffusion of carbon in silicone is very slow. The novel RTP can be successfully applied in technological processes of fabrication of films and layers on silicon substrates as well as to study graphene transformations.
2. Model
We consider a structure of a thin conductor film on a silicon substrate in a uniform RF magnetic field normal to its surface (Fig. 1). For simplification, we assume that the length of the structure is much larger than its width, i.e. the specimen has the form of a strip.

Fig. 1. Configuration of a conducting layer/silicon substrate structure in magnetic field.

The expressions for the heat generation $W$ (averaged eddy current loss power per unit area of the structure surface [1]) and heat transfer $Q$ from the surface (the Stefan-Boltzmann law) are

$$W = K(\mu_0 H_0 L)^2(\frac{d_{Si}}{\rho_{Si}} + \frac{d_c}{\rho_c})$$

$$Q = \sigma T^4 - \sigma T^4_{room}$$

where $K$ is the specimen shape coefficient, e.g. equalled $1/24$ for a long strip, $\mu_0$ is the vacuum magnetic permeability, $H$ and $\omega$ are the amplitude and the angular frequency of the external magnetic field, $L$ is the characteristic size of the specimen (strip width), $\sigma$ is the Stefan-Boltzmann constant, $d_{Si}$, $d_c$, and $\rho_{Si}$, $\rho_c$ are the thicknesses and resistivities of the Si substrate and conducting layer, respectively.

The thermal state of the structure is approximately described by the following equation

$$CdT/dt = W - Q$$

where $T$ and $C$ are the averaged temperature and total heat capacity per a unit area of the structure, respectively.

3. Analysis of RF heating
In Fig. 2 presents the typical dependences of the heat generation $W$ and heat transfer $Q$ on the structure temperature. If the thickness of the conducting layer is sufficiently small such as $d_{c1}$ (curve 1), the system is heated up to a finite temperature $T_S$ corresponding to point S. The thermal state corresponding to this point is stable. Point G is another stationary state but is unstable. With increasing the conducting layer thickness the stationary points move toward and at a critical thickness $d_{c2}$ (curve 2) these points merge. No stationary state exists for a conducting layer with thickness larger than the critical thickness $d_{c2}$; temperature increases unrestrictedly (curve 3). In this case, heating of the conducting layer/silicon substrate structure obeys the explosion law.
Fig. 2. Heat generation $W$ and heat transfer $Q$ temperature diagrams. Heat generation for different thicknesses of graphene layer is shown by curves 1, 2 and 3, whereas curve 4 represents the heat transfer.

The main result of the qualitative analysis is: there are two essentially different heating regimes of the structure: a) the stationary regime with a constant temperature; b) the non-stationary heat explosion regime with an unlimited increase of the structure temperature.

The conditions for realization of the regimes can be represented as [2, 3]:

a) the stationary regime with a constant temperature is achieved at

$$R□/(H\omega L)^2 > A,$$

where $R□ = \rho /d_c$ is the sheet resistance of a conducting layer.

Here $A$ is constant that can be calculated from the parameters of the structure [3]:

$$A = \mu_0 \gamma c K \beta_0^2/((\sigma \Theta)^2)$$

where $\Theta = k_BT_1^2/E_a$; $\beta_0 = T_1/\Theta$, $\beta_1 = T_1/\Theta$; $\gamma c \geq (1+\beta_1)/([\beta_1^2(\beta_1^2 - 4\beta_1^3 - \beta_0^4)]$. Here the characteristic temperature $T_1$ is determined as a temperature at which the loss power in the conducting layer and the substrate are equal: $d_s/\rho_s(T_1) = d_c/\rho_c(T_1)$. Activation energy is determined by the expression $\rho_s = \rho_s0\exp(+E_a/k_BT)$. A detailed description of the criterions Eqs. (4) – (6) is presented in [3].

The obtained results can be applied to analysis of thermal state of structure with any conducting layer.

In the next section the theoretical prediction will be compared with experimental results with Ta-Ti layer, and then we will discuss the explosion regime for monolayer graphene/silicon structures.
4. Experiment with Ta-Ti film/Si substrate structure
Experimental realization of the explosion regime was performed using the Ta – Ti film/Si substrate structure [2]. Substituting our experimental parameters, for which the heat explosion was realized $H = 12000 \, \text{A/m}$, $f = 13.5 \, \text{MHz}$, $L = 0.005 \, \text{m}$, $R_c = 12.2 – 23.4 \, \Omega/\square$, in to (6) we obtain

$$A_{\text{theor}} = 18 \times 10^{-19} \, (\Omega/\square)(\text{sec}/\text{A})^2.$$ 

This value is in reasonable agreement with the critical parameter estimated from the experimental data

$$A_{\text{exp}} = (4.7 - 9.0) \times 10^{-19} \, (\Omega/\square)(\text{sec}/\text{A})^2.$$ 

In [3] it was shown that the heating in the explosion regime can be separated in two stages. In the first stage the structure is slow heated, while in the second stage the sample is fast heated, theoretically up to an unlimited value. The theoretical predictions are well confirmed by experiment with the Ta-Ti film/silicon substrate structures, parameter $R_c/(H\omega L)^2$ of which is less than the critical value (Fig. 3). The detailed description of the experiments is presented in [2].

![Fig. 3. Ta-Ti film/ Si substrate structures after RF heating in the heat explosion regime, parameter $R_c/(H\omega L)^2$ less than the critical value: a) no melting; magnetic field was switched off before a fast unlimited heating; b) melting at substrate edges; to prevent the sample destruction the field was switched off in the initial stage of the fast unlimited heating [2].](image)

5. Evaluation of heat explosion in nano-graphene layer/Si substrate structure
The sheet resistance values of two monolayer graphene films were measured as $26.97 \, \Omega/\square$ and $61.7 \, \Omega/\square$ [5]. These experimental values are close to the sheet resistance of $R_c = 12.2 – 23.4 \, \Omega/\square$ in our experiments which confirmed the explosion regime. Note that variation of the frequency or/and amplitude of the RF field, or structure sizes allows one to achieve the heat explosion regime for conducting layer with the sheet resistance varying in a wide range. This points to a real opportunity to realize the heat explosion regime for a graphene layer/silicon substrate structure.

6. Summary
The RF heating of the conducting layer/silicon substrate structure was analysed. It is shown that two regimes of the RF heating of these structures can be realized: the first one is characterized by heating of the structure up to a finite temperature; the second regime corresponds to a fast unlimited temperature increase (heat explosion). The criterions of realization of these regimes are presented in analytical form. Using these criterions and the experimental data for the sheet resistance of the monolayer graphene it was shown the possibility of the heat explosion regime for graphene layer/silicon substrate structures at RF heating.
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