Formation of a Corrugated Graphene Substrate on the Paraffin Surface

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Abstract. In this paper, we propose a method of creating a wave-like corrugated surface from graphene nanoparticles. Due to the Kelvin-Helmholtz instability, the graphene suspension flowing onto the melted paraffin forms a wave-like surface. The inhomogeneity wavelength \( \lambda \) can be controlled by changing the relative surface tension.

1. Introduction
The great interest of researchers to the study of the properties of graphene films is associated with their possible applications in nanoelectronics. Thus, [1, 2] have shown that fluorination of the outer side of graphene leads to its deformation. Such surface deformation forms corrugations several tens of nanometers deep. This corrugated surface allows the formation of a substrate with predetermined areas for the sorption of metal atoms. To manufacture graphene-based devices, for example, memristors, not a single corrugation, but a corrugated area with a large number of ordered corrugations is required.

Under the influence of the Kelvin-Helmholtz instability mechanisms, with fluid flowing at the interface, we can expect formation of a wave-like structure [3]. When hydrocarbons interact with the graphene suspension, a transition layer from graphene nanoparticles and hydrocarbon molecules is formed at the interface [4]. The task of this work is to experimentally obtain thermocapillary waves in a film of graphene nanoparticles on a substrate of hydrocarbon paraffin molecules.

2. Experimental technique
The hydrocarbons used were molten paraffin, the molecules of which adsorbed on graphene particles. Within 24 hours, the molten paraffin and graphene suspension were exposed to a temperature of 56°C inside a thermostat (Fig. 2). After that, a film from graphene particles and hydrocarbons was formed at the interface. Further, the coordinate table was inclined at a small angle to ensure a slow (Re \( \leq 1 \)) film motion relative to the interface. Then, the temperature was slowly decreased, while the temperature gradient on the film surface was maintained at approximately 1K/mm.
Figure 1. Installation for the formation of capillary waves at the interface of a graphene suspension - paraffin [5]

3. Results and discussion
The Fig. 2 shows the image of the graphene film surface on the frozen paraffin obtained with a scanning atomic force microscope (AFM) in a semicontact mode. The film forms thermocapillary structures in the form of waves, with a long inhomogeneity $\lambda = 750 \pm 20$ nm. Thus, as a result of exposure to thermocapillary forces, the film surface suffered deformations resulting in a transition to a structured flow.

Figure 2. Thermocapillary waves at the interface of paraffin - graphene suspension

The results of the experiment can be considered as a manifestation of the Kelvin-Helmholtz instability [3]. According to the experimental conditions, liquid paraffin begins to move along the surface of the graphene aqueous suspension. Such movement forms a disturbance that creates wave deformation of the interface.

Consider two incompressible liquids - molten paraffin, lying on a graphene aqueous suspension, then the initial hydrodynamic equations are:

$$\rho_1 \frac{dv_1}{dt} = -\nabla p_1 + \rho_1 g,$$

$$\frac{dp_1}{dt} = 0, \ \text{div} V_1 = 0; \ \text{for paraffin} \quad (1)$$
\[ \rho_2 \frac{dV_2}{dt} = -\nabla p_2 + \rho_2 g, \quad \frac{d\rho_2}{dt} = 0, \quad \text{div}V_2 = 0; \] for water suspension of graphene \hspace{1cm} (2)

where, \( \rho_1 \) - paraffin density \((920 \text{ kg/m}^3)\), \( f_1 \) - specific Van der Waals force acting on paraffin from the side of graphene, \( \rho_2 \) - density of graphene water suspension \((950 \text{ kg/m}^3)\), \( f_2 \) - specific Van der Waals force acting on graphene from the side of paraffin.

In the framework of the proposed model, the following is true:

\[ \rho_1 \frac{dV_1}{dt} = \rho_2 \frac{dV_2}{dt} \hspace{1cm} (3) \]

It's obvious that \( p_2 = p_1 + p_0, \) \( f_1 = f_2 = f \), then from (1) (2) we get:

\[ \nabla p_0 = g(\rho_2 - \rho_1); \hspace{1cm} (4) \]

In equilibrium position from (4) it follows:

\[ \frac{dp_0}{dz} = -g(\rho_2 - \rho_1); \hspace{1cm} (5) \]

Let us transform equation (5) in a standard way and obtain the dispersion equation:

\[ \omega^2 = gk + \frac{\sigma k^3}{\rho_2 - \rho_1}; \hspace{1cm} (6) \]

where, \( \sigma \) - relative surface tension of paraffin and water.

Solving equation (6) for an extremal value of \( k \), we get:

\[ k = \sqrt{\frac{(\rho_2 - \rho_1)}{3\sigma}}. \hspace{1cm} (7) \]

Then, the length of the capillary waves, \( \lambda = 2\pi/k \), depends on the density of the liquids and the relative surface tension \( \sigma \). Consequently, by changing the \( \rho \) and \( \sigma \) parameters, one can control the inhomogeneity wavelength \( \lambda \).

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