QUALITATIVE ASSESSMENT OF THE UV EXPOSITION PROCESS NEAR THE DIFFRACTION LIMITS

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Abstract. *Optical lithography is one of the most common microfabrication methods. A major limitation of photolithography is a diffraction phenomenon, which affects the falsities in dimensions and shape of designed structures, due to the light bending on the mask edges. In the presented work, the technological parameters that influence the shape of the resist structures are reported. The experimental results are compared with the simulations results, based on the solution of Maxwell's equations using the RF module of COMSOL Multiphysics software. The electric field intensity distribution in the resist layer was analysed for the mask slits that are larger and comparable to the applied wavelength. The differences in wave energy absorption in the resist layer are presented and discussed. For both cases, the impact of the chromium film thickness of the mask on the pattern profile of the resist is studied, and the comparison is performed between the simulation and experimental results.*

Keywords

Diffraction limits, simulations, UV exposition.

1. Introduction

Nowadays, strong development in microelectronics implicates the necessity of reducing the critical dimensions in microfabrication technologies. This is the substantial challenge for optical lithography, that is the basic and the most important microfabrication process. The resolution in photolithography is limited by physical restrictions that result from the applied electromagnetic radiation wavelength. This is formulated as the Rayleigh limit [1]. It indicates that the minimum feature dimension that could be fabricated is generally comparable to the wavelength [2]. To obtain higher resolution, changing the wavelength and the system is often required. The lithography methods that are based on a shorter wavelength – DUV and EUV – allow to achieve a smaller structure size. However, these methods may cause many of the other problems [3] and [4].

In photolithography, except for the main limitation, a resolution enhancement could be also obtained in other ways. One of the factors that has an impact on the features' dimension is the distance between the mask and the resist layer. The shorter distance ensures the smaller diffraction effects, and due to this, the higher resolution and the better pattern precision [5]. Hence the vacuum contact system is most often used. The same can be said for the influence of the resist's thickness on the pattern resolution. The thicker the photopolymer layer is, the more difficult it is to obtain the required structure width in the entire depth of the layer [6].

Other factors that affect the size of features refer to the photolithographic mask features. The pattern density at the mask is related to the exposition area errors, in particular for high structure density [7]. Besides, the opaque mask layer, depending on the metal thickness, has different transparency and different intensity of electric field going through respective areas. This can cause changes in the polymer's structure, not only in the defined fields. Generally, the 40 nm of the chromium layer is the minimum metal thickness that is sufficient to fully block the UV light [8] and [9]. Typically, photomasks with 100 nm of Cr are widely used to ensure zero transmission and guarantee mechanical strength and abrasion resistance.

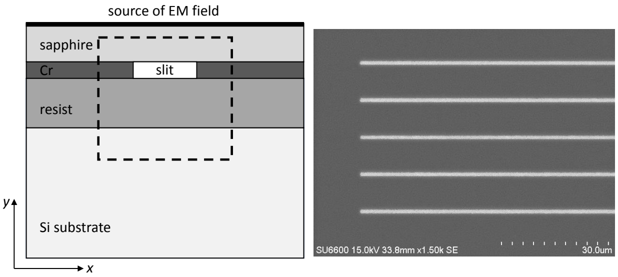
In the paper, the technological parameters that have an influence on the shape of resist structures were studied and described. The impact of the dimension of mask slits on the resist pattern profile was presented.

The thickness of the opaque mask layer was reported to be significant for proper exposition of the resist. The observed phenomena were also analysed with the use of simulations of the electric field intensity distribution.

2. Experimental Details

The structure applied for the numerical investigation was similar to that used in the experimental part of the research. It consists of a linear source of electromagnetic field, a mask – a chromium layer with structures deposited on a sapphire substrate (a single slit with the same width as the designed test window width), and silicon substrate covered with a polymer layer (Fig. 1(a)). The examined area was presented as the dash line.

The analysis of electric field intensity distribution in the lithography system was made by solving Maxwell's equations with the finite element method. For this purpose, the RF module of COMSOL Multiphysics software was used. The used wavelength was 405 nm. The electromagnetic field propagation was determined along the Y-axis.



(a) (b)

Fig. 1: The lithography system used for simulations (a) and a fragment of the applied mask pattern (b).

The simulations were conducted for two masks with different chromium thicknesses of 50 nm and 100 nm and two slit widths of 500 nm and 1 µm, respectively. We observed the difference in electric field intensity distribution for the slits, which was comparable with the wavelength and more than twice as large.

The impact of changes in the polymer layer structure during the exposure process was not included in the simulations.

In the experimental part of the examination, the dedicated sapphire-chromium masks with test structures were designed and fabricated according to the elaborated technology [10]. The test pattern consisted of a series of equidistant lines of 500 nm, 1 µm, and 2 µm wide. The distances between the slits were specified on 10 µm to avoid the proximity effects (Fig. 1(b)). The chromium layer thickness was 50 nm and 100 nm, respectively.

In addition, the transmission rate through the Cr layers was measured using an optical intensity detector.

The photolithography processes were conducted using fabricated masks. The silicon substrates were chemically cleaned using RCA procedure and baked at 200 °C. The commercially available ARP 3120 resist with a layer thickness of 600 nm was applied on it by spin-on. The rotation speed 4000 rpm, tempering temperature 100 °C, and baking time 60 s were applied. The exposition was carried out with the Carl Suss MA-56 lithography system. The wavelength of used UV light was 405 nm, and the light intensity was 9 mW·cm^2. The patterns were transferred to the substrate in a vacuum contact mode to minimize the distance between the mask and the substrate. After irradiation, the structures were developed by applying an appropriate solution. The fabricated structures were examined with an optical microscope and Atomic Force Microscope (AFM). The AFM tapping mode was used. Measurements were made repeatedly in the middle of each lithography window in 2 modules of 5 lithography windows. The width and height of the structures were measured in the cross-sections of the resist windows obtained from the AFM measurements, as presented in Fig. 2. The width of the windows was measured at the half of its height.

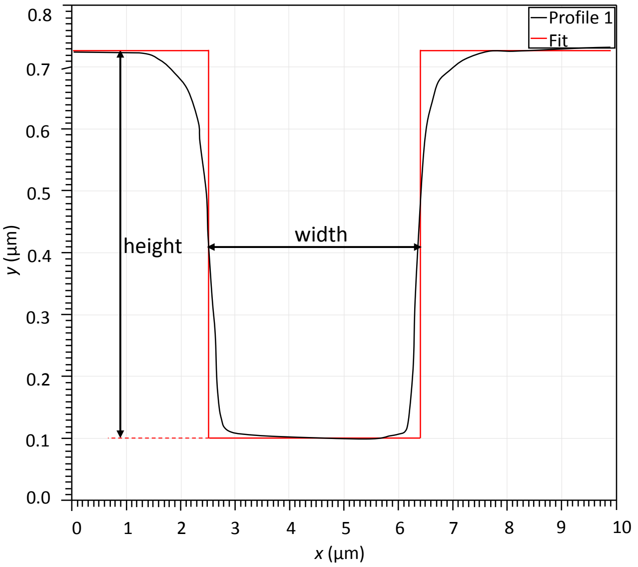
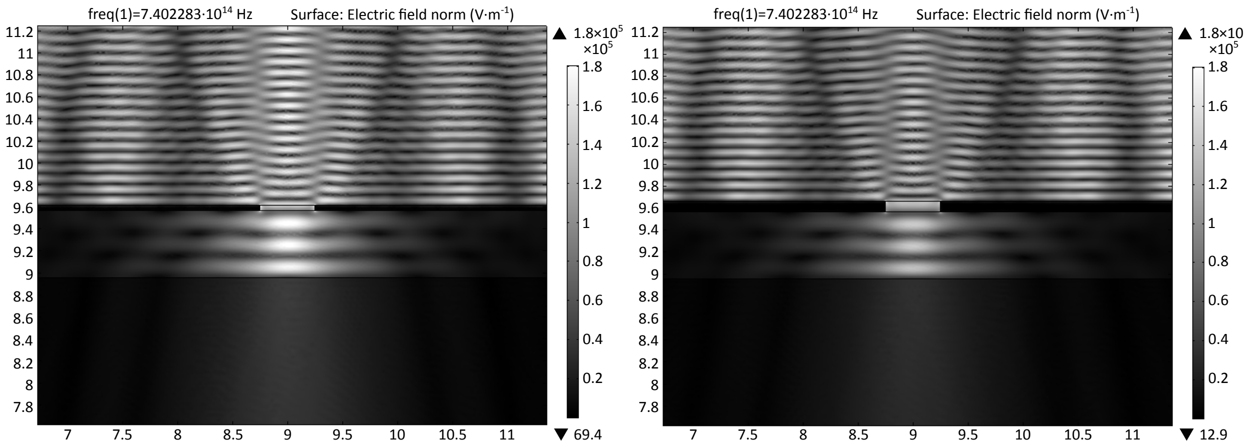


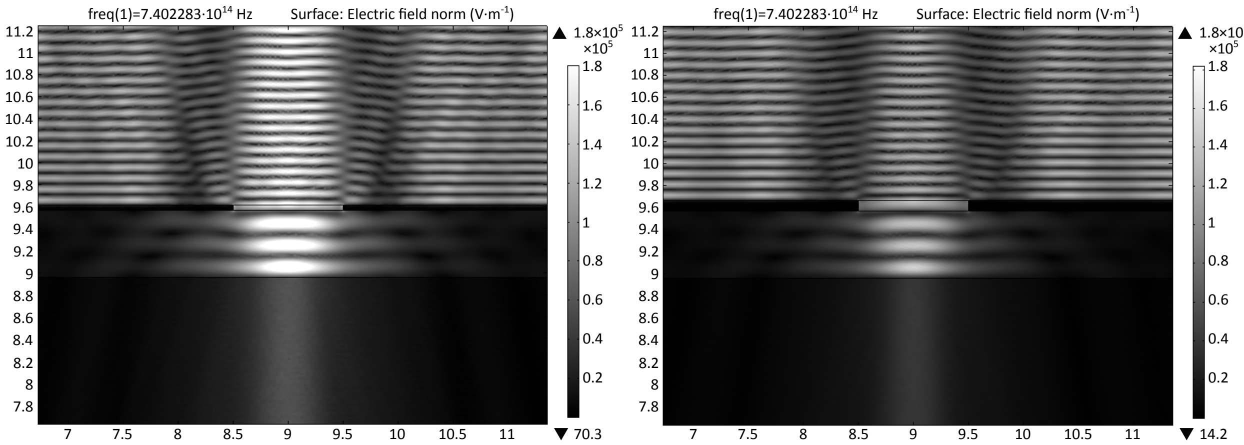
Fig. 2: Diagram of the resist structure cross-section from AFM measurement with the window width measurement location specified.

3. Results

As a result of the conducted simulations, the distribution of electric field intensity in the lithography system was obtained. The differences for various slit widths and chromium mask thicknesses are presented in Fig. 3.



(a) 500 nm slit, 50 nm Cr. (b) 500 nm slit, 100 nm Cr.



(c) 1000 nm slit, 50 nm Cr. (d) 1000 nm slit, 100 nm Cr.

Fig. 3: The electric field intensity distribution in the lithography structure for the designed slit widths and chromium mask thicknesses as depicted.

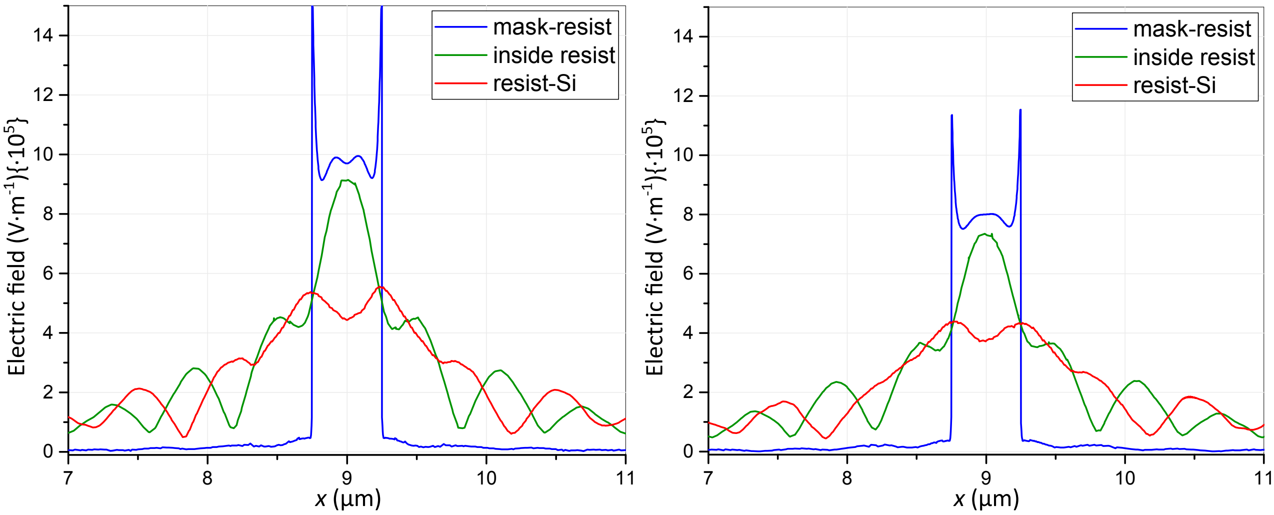
The electric field intensity distribution presents the expected diffraction on the mask edges. This light bending causes the widening of the region where the resist structure is modified. Moreover, the diffracted light reflects from the silicon surface and from the Cr layer, which also affects the enlargement of the exposed area. The phenomenon is more pronounced for smaller gaps. Besides, the differences in light intensity, which can result from the interference of electromagnetic waves are clearly seen for 50 nm and 100 nm of the Cr opaque layer.

Additionally, to analyse the diffraction at the chromium layer edges, the behaviour of the electromagnetic field, while passing the slit, was evaluated at three horizontal lines of the lithography system. The electric field profiles were located between the Cr layer and the polymer, at half the depth of the polymer layer and at the polymer – silicon border. The results are compared in Fig. 4.

As presented, the higher electric field intensity is observed for the 50 nm Cr thickness, which can result from the interference of the incident and the reflected wave. This intensity increase, depending on the polymer contrast curve, may affect the resist structure modification. This observation leads to the conclusion that changes in lithography system geometry influence the electric field distribution. By using a photolithography mask with slightly different Cr layer thickness or different resist thickness, it is possible to modify other technological parameters, such as light intensity or development time, to obtain the same results.

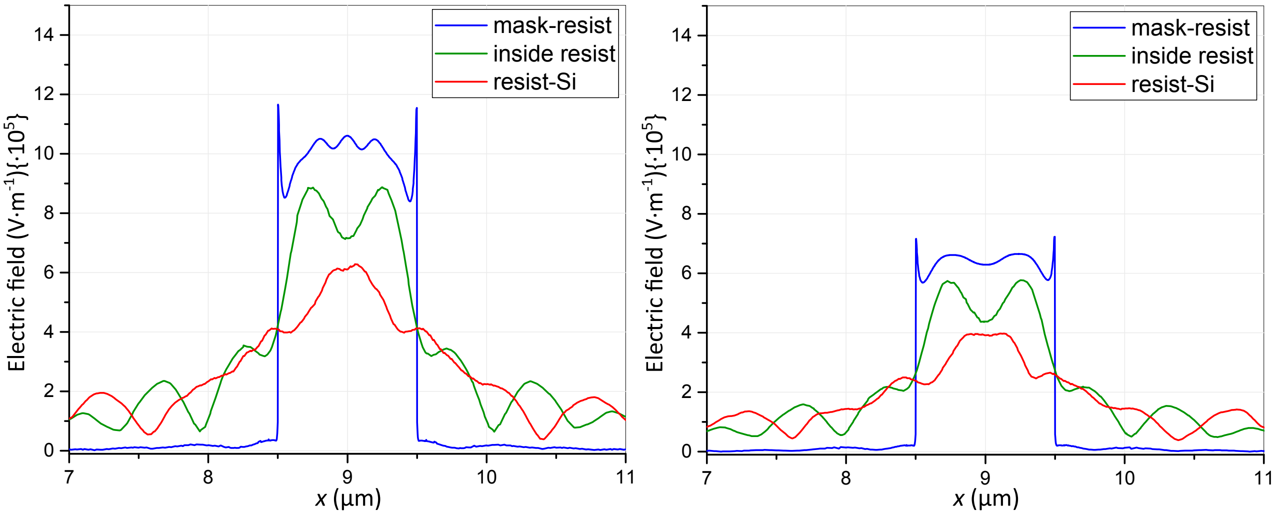
Moreover, the simulation results showed the electric field intensity to be higher when passing through slits that are comparable to the wavelength. Inside the resist, a closer silicon substrate corresponds to a reduced electric field intensity, but the radiation area, due to the diffraction, expands.

As a result of the experiment, the windows in the resist, of various width for the different mask thicknesses, were obtained. For each sample, the windows enhancement was measured, and the mean value and standard deviation were determined for each pattern



(a) 500 nm slit, 50 nm Cr.

(b) 500 nm slit, 100 nm Cr.



(c) 1000 nm slit, 50 nm Cr.

(d) 1000 nm slit, 100 nm Cr.

Fig. 4: The electric field intensity profiles at 3 different depths in the lithography structure for designed slit widths and chromium mask thicknesses as depicted.

size. To compare the experimental and the numerical calculations, the relative pattern enlargement in the experiment and simulations are presented in Fig. 5. The windows' width measurements were made in the half of the windows' height, both in the experimental work and the simulations.

The largest relative pattern enlargement was observed for the smallest gaps, which were comparable to the wavelength. The average width of these structures was even three times larger than the nominal width that was designed at the mask. For other slit widths, the enlargement was not so relevant, however, the structures were still approximately twice as large. As marked, a similar relationship was observed for the simulation results. The research showed a significant impact of slit dimension on the resolution of the structures. For slits comparable to the wavelength, the diffraction phenomenon is more explicit. This affects the considerable enlargement of the structures, which was also confirmed by the simulation results.

The slight discrepancies in the experimental and numerical results occur because the experiment was not optimized due to the development process and exposition time. Nevertheless, in accordance with the theoretical assumptions of the lithography process, the width of the windows fabricated in the resist increases when the exposure time is increased; however, the tends remain the same.

In Fig. 6 the fragments of the resist windows measured with the AFM are presented.

Additionally, the thin line of resist inside the open window in the polymer was observed for the 1 µm

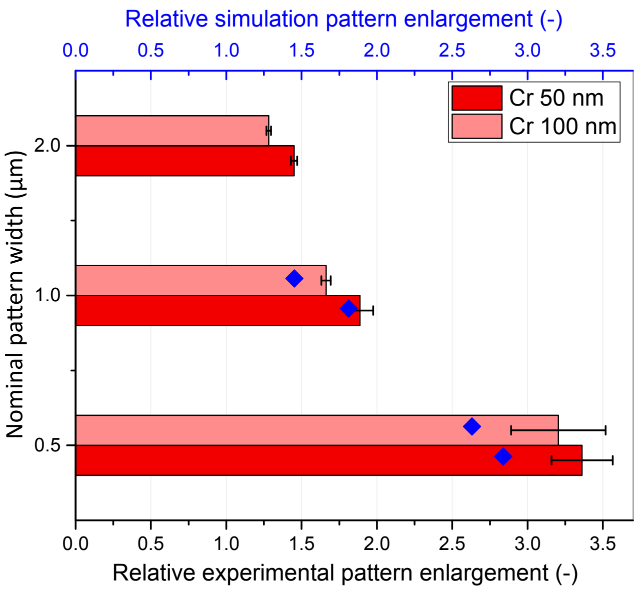
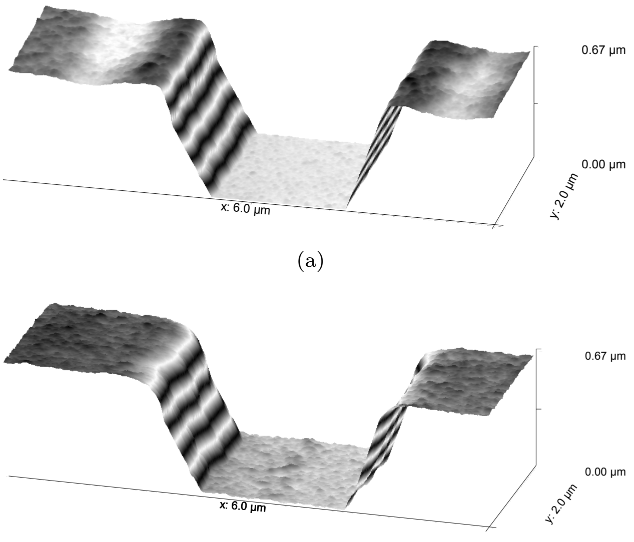


Fig. 5: Relative pattern enlargement for different Cr thicknesses and structure sizes.



(a)

(b)

Fig. 6: The AFM profile of the 500 nm slit for the 100 nm Cr (a) and for the 1000 nm slit and 100 nm Cr (b).

structures. This observation was confirmed in the simulation and shows the impact of a slight decrease of electric field intensity in the resist layer near the middle of the exposing area (Fig. 6(b)) and could occur for non-optimized other process parameters.

The slopes of the side walls differ from the slope resulting from the simulation, which is caused by the nature of the development process and the dissolving of the material near the resist window edges.

Additionally, to verify the layers' opaqueness, the transmission was measured. The results are collated in Tab. 1.

Tab. 1: The transmission through the Cr layers of 50 nm and 100 nm thickness ($\lambda = 405$ nm).

Cr layer thickness	**Transmission (%)**
50 nm	$102.9 \cdot 10^{-6}$
100 nm	$3.1 \cdot 10^{-6}$

The transmission level for both Cr layer thicknesses proved to be fully opaque for the UV light. Nevertheless, the examination results for different chromium layer thicknesses allowed us to observe a larger exposition area for the thinner 50 nm Cr thickness. These results are similar to the simulation results and indicate a slightly higher interference for the thinner metal layer when other geometry parameters are the same.

Moreover, the resist structures height was measured. The results are presented in Fig. 7.

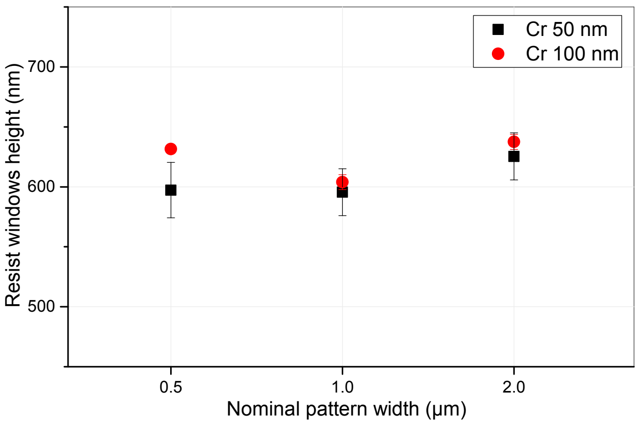


Fig. 7: Resist structures height for different Cr thicknesses and structure sizes.

Smaller resist windows' height can be observed for structures exposed with the mask with 50 nm Cr layer. This observation confirms the greater interference phenomena for lithography system with thinner metal layer at the mask. The light bends passing through the mask slit, propagates inside the resist and reflects from the silicon border, affecting the exposed area enlargements. The backlight causes the change in resist structure even in the upper part of the polymer. During the development process, due to the contrast curve, the exposed area dissolves in the developer.

In the theoretical analysis, the influence of the development process and changes in the polymer structure during exposure on the resolution of structures was not reflected, and therefore the presented research is qualitative.

4. Conclusions

In the paper, the technological factors that influence the shape of the resist structure during optical lithography were presented and discussed. The simulation and experimental results were compared. The quality consistency of the experimental results and the simulated electric field intensity distribution were obtained. The research revealed a significant impact of the opaque layer thickness and structure width on the width of windows produced in the resist layer. It was found that the change in the process of pattern formation and the occurrence of pattern enlargement for structures comparable with the used wavelength results from the diffraction of light, which is more explicit for smaller slits. The numerical analysis illustrated the impact of optical phenomena like diffraction and interference on the electric field intensity distribution in the polymer layer, which directly affects the shape and resolution of the resist structure in the lithography process. Furthermore, the simulations revealed the change in electric field intensity level for different lithography system thickness due to the different thicknesses of the Cr layer. The AFM measurements confirmed the quality variability of the created structures for different Cr thicknesses, which results from different interference. The use of both, 50 nm and 100 nm Cr layer, was found justified due to the high opacity of both layer thicknesses. The research proves the need for further examinations in order to understand the phenomena relating to the diffraction limits fully and to control the fabrication of submicrometer structures using optical lithography consciously.

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