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Critical impact of mask electromagnetic effects on optical proximity corrections performance for 45 nm and beyond

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Numerous studies have addressed the challenges ahead in optical lithography due to electromagnetic effects in photomasks (so-called emf effects), which arise from the complex interaction of the illumination with mask topography whose size now approaches the wavelength. As design critical dimensions shrink, the electromagnetic response of the reticle becomes a complicated function of the incident polarization with serious impact to printed critical dimension (CD) on the wafer. A number of modeling techniques are available to approximately account for emf in the process models employed during optical proximity correction calculations, with small to moderate runtime penalty. Among them are simple mask CD bias, the boundary layer [J. T. Azpiroz *et al.*, Proc. SPIE **5040**, 1611 (2003)], the domain decomposition method [K. Adam and A. Neureuther, Proc. SPIE **4562**, 1051 (2001)], and techniques based on the geometrical theory of diffraction [G. K. Chua *et al.*, Proc. SPIE **5377**, 1267 (2004); A. Khoh *et al.*, J. Opt. Soc. Am. A **21**, 959 (2004)]. In this article several of these techniques are benchmarked in terms of accuracy and range of applicability. Results are compared against rigorous electromagnetic simulations. © *2007 American Vacuum Society.* [DOI: 10.1116/1.2429667]

I. INTRODUCTION

Diffraction from the polygonal openings in the absorber films of lithographic photomasks has traditionally been modeled using the so-called thin mask approximation (TMA) derived from the application of Kirchhoff's boundary conditions to the electromagnetic fields on the exit surface of the photomask. The TMA field is the product of the incident field with the ideal transmission function of the mask layout as illustrated in Fig. 1(a), thus ignoring strong electromagnetic scattering arising at the topography edges as shown in Fig. 1(b), but still providing accurate results for mask dimensions several times larger than the wavelength. State of the art optical lithography, however, employs deep ultraviolet light at 193 nm wavelength and 4× demagnification factor to print dimensions as small as 45 nm on the wafer, which implies wavelength-sized mask dimensions and subwavelength dimensions for nonprinting mask features used for resolution enhancement.[1] As a consequence, electromagnetic diffraction from the photomask differs from Kirchhoff's prediction, inducing polarization dependent amplitude and phase errors in the lithographic models used during optical proximity correction (OPC) calculations.

The benefits of applying a simple mask critical dimension (CD) bias to the phase shifting openings of alternating phase shifting masks (alt-PSMs) have long been recognized in optical lithography as a means to correct imbalances in the transmission of these openings compared to non-phase-shifted openings.[2] Phase depth biasing and undercutting of the etched quartz have also been used to enhance transmission and correct for phase errors, but the required underetch and other manufacturing limitations make depth and undercut biasing impractical for 45 nm and beyond. These techniques have prolonged the applicability of the computationally efficient TMA during OPC calculations for alt-PSM technology, but they continue to ignore scattering losses on the Cr edges of the alt-PSM mask film stack. Similarly, electromagnetic edge scattering in attenuated phase shifting mask (atten-PSM) or binary masks has usually been ignored within OPC models, effectively shifting the anchoring dose. As minimum pitch and critical dimension continue to shrink, neglect of emf during OPC can translate into large CD errors for both alt- and atten-PSMs that can no longer be compensated by dose adjustments.

We now consider biases of a subtly different kind, namely, biases that are applied only in TMA simulations, to approximately mimic emf effects with minor impact on efficiency; these simulation biases do not involve physical adjustments of the fabricated mask. A simple mask CD bias is an efficient yet reasonably accurate technique to account for emf effects on absorber edges on the mask. In this article, we will refer to simulation biases applied to absorber edges as *absorber bias*. Alt-PSMs employ additional phase shifting openings on the mask that are manufactured by etching into the glass to the appropriate depth, as illustrated in Fig. 1(b). emf effects in the etched glass need to be modeled with a different bias (referred to as *shifter bias*), which is used in

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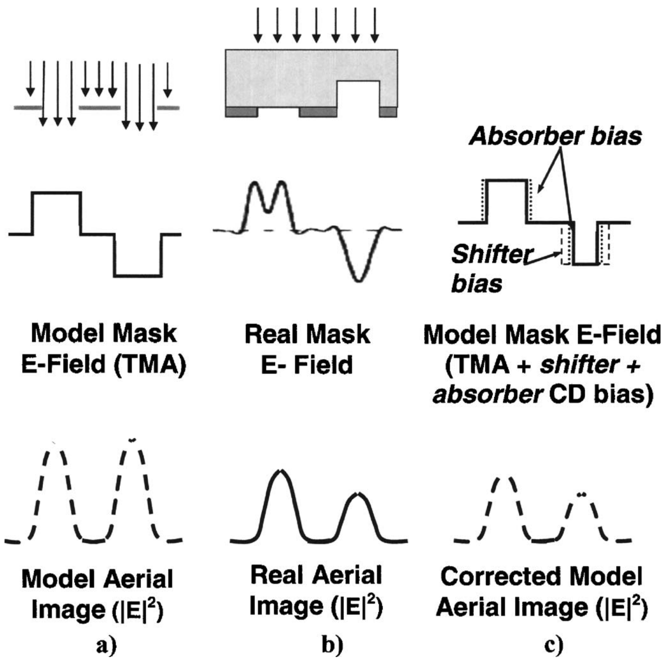
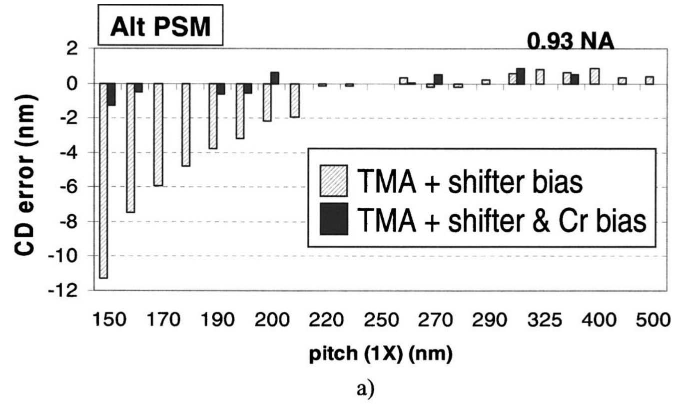


FIG. 1. Schematic illustration of the mask field and the aerial image produced by (a) the thin mask approximation (TMA), (b) the real electromagnetic fields on the mask, and (c) the thin mask approximation with absorber and shifter CD biases. The shifter bias is applied to the 180° shifter opening to model amplitude losses, and the absorber bias is applied to every edge (all polarities) to model scattering losses.



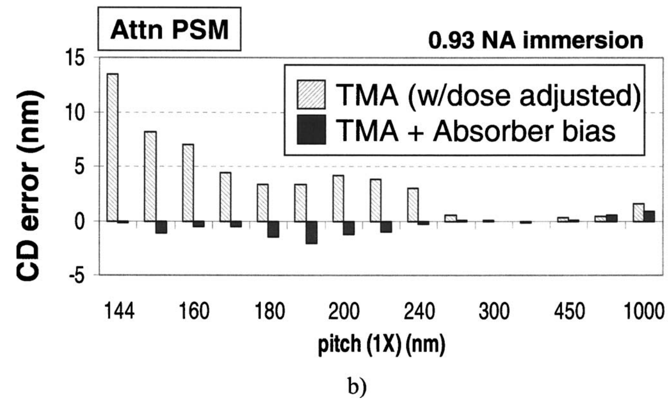


FIG. 2. Through-pitch error in wafer CD calculated using a calibrated lumped parameter model resist model, for two sets of mask dimensions, from images calculated using TMA, and TMA with bias. (Rigorous emf simulations are used as a reference.) Two RETs are analyzed: (a) alt-PSM and (b) atten-PSM with a target dimension of 50 nm.

conjunction with the absorber bias due to the absorber edge scattering as in Fig. 1(c). These bias definitions refer to isotropic compensations common to both polarization states when unpolarized illumination is employed. In this article, we explore the range of applicability of the simple (isotropic) mask CD bias to compensate for emf effects during simulations of attenuated and alternating phase shifting masks, and contrast its inability to model phase errors with the accurate performance of more sophisticated approaches.

A. Simple bias

Rigorous electromagnetic simulations were carried out using PROLITH 9.3 (KLA-Tencor) to assess the OPC impact of neglecting emf. Using a calibrated lumped parameter model, three sets of OPCed mask spaces were calculated for printing a 50 nm linewidth through pitch at 0.93 NA (numerical aperture), using two different mask technologies. For alt-PSM (and partial coherence 0.2σ unpolarized illumination), one set of OPCed mask spaces was calculated using rigorous emf simulations, a second set using TMA with shifter mask CD bias to account for transmission imbalance, and a third set using TMA with both shifter bias and absorber bias (applied appropriately on every edge, i.e., phase shifting spaces were biased by the sum of the absorber and shifter biases). Finally, the linewidth printed by each mask was simulated using rigorous emf. The CD errors in the results with OPC based on TMA with each kind of bias are plotted in Fig. 2(a). The anchor dose for the OPC results using only a shifter bias was adjusted for zero linewidth error at 250 nm pitch; nonetheless, the errors at tighter pitches are significantly larger than those for the OPC set calculated using both biases.

Figure 2(b) shows a similar analysis for atten-PSM masks (annular partial coherence of $0.55\sigma_{\text{in}}-0.85\sigma_{\text{out}}$ and unpolarized illumination). Three sets of OPCed mask spaces were simulated through pitch with rigorous emf, pure TMA, and biased TMA (with a single absorber bias applied on every edge). The anchor dose for the OPC set that used pure TMA was adjusted for zero resist space error at 300 nm pitch. Despite the dose adjustment, the pure TMA OPC values still produce significant errors at the smallest pitches, where errors due to emf couple to larger mask error factors. However, a simple opaque emf mask CD bias applied to all feature edges at each OPC iteration compensates the effect of emf fairly well (in these best focus images), and significantly reduces OPC error with minimal alteration in OPC procedure.

Mask emf effects are polarization dependent; nonetheless, a single opaque CD bias correction was applied for both polarizations in the Fig. 2 calculations, as a nonrigorous average of TE and TM effects under unpolarized illumination.

II. EFFECTS OF MASK TOPOGRAPHY ON CRITICAL DIMENSIONS

A simple mask CD bias model of edge scattering losses is an attractive solution for OPC simulations, given its simplicity and speed. To determine the range of applicability of the simple bias model, the mean absolute CD error in the aerial image produced by biased TMA compared with rigorous emf simulation was calculated across the aerial image profile. Then the rms CD error across pitch was estimated for several mask line and space sizes, at both nominal focus and ±100 nm defocus. It was observed that a simple 5 nm (1 ×) CD bias produce rms errors of about 1 nm or less at best focus, and 2 nm or less out of focus, for mask lines as small as 30 nm (1×). The rms error for mask spaces likewise remains bounded by 1 nm at best focus, for spaces as small as 60 nm (1×). However, the rms error from the bias model exceeds 2 nm for defocused spacewidths below 70 nm (1 ×). Error levels of this small magnitude are significant in optical proximity simulations. Image quality further degrades at the smallest spaces, as does the modeling performance, and application of the simple bias model to spaces 50 nm or smaller produces large errors with defocus as well as at best focus conditions, limiting its applicability for OPC.

As lithography moves into a regime of hyper-NA imaging, the so-called Hopkins approximation (which assumes that a tilt in illumination merely tilts output orders) has been shown to introduce non-negligible errors in the aerial image. Repetition of the above calculations without the Hopkins assumption did not change the conclusions described. However, the Hopkins approximation was found to introduce a systematic 0.5 nm error (1×, per CD) in the bias value required for optimum fit, which is consistent with recent observations of an increase in threshold to size from the Hopkins approximation.[3] A possible implication for OPC is a runtime penalty proportional to the number of regions into which the source pupil must be divided to account for the non-Hopkins dependence on angle of incidence.[3]

The focus dependency observed in the aerial image fit indicates phase shifts in the light diffracted by the photomask that a simple bias cannot compensate. Phase errors due to emf effects in attenuated phase shifting masks will shift the position of best focus in a polarization dependent manner[4] as the space dimension decreases. A polarization dependent focus shift was observed [Fig. 3(a)] when 70 nm atten-PSM spaces at 160 nm pitch were imaged on a 1.2 NA 193 nm full field scanner (ASML XT:1700i). Measurements were taken with an Applied Materials NanoSEM from wafers exposed with partial coherence $0.55\sigma_{in}-0.85\sigma_{out}$ annular illumination under X or Y polarization. Rigorous emf simulations qualitatively matched the experimental data in Fig. 3(b).

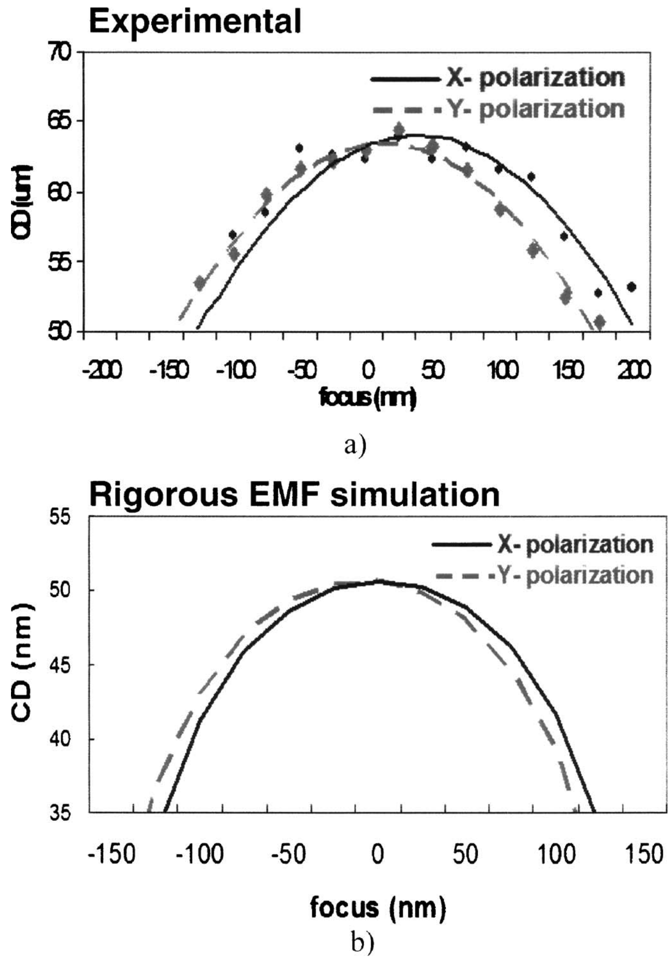


FIG. 3. (a) Bossong curves for a 70 nm space, 160 nm pitch exposed with annular $0.56\sigma-0.85\sigma$ and 1.2 NA and X and Y polarizations, respectively. (a) Experimental results; (b) rigorous emf simulation results.

III. MODELING OF EMF EFFECTS DURING OPC

Rigorous modeling of electromagnetic phenomena on the photomask will be of critical importance in defining optimal resolution enhancement techniques (RETs) at or below 45 nm. A simple isotropic opaque CD bias can largely compensate the error in amplitude transmission from simple TMA, but it fails to accurately capture the phase errors that arise with small spaces. In this section we briefly analyze alternative modeling approaches for OPC. More accurate methods include the boundary layer,[5] the domain decomposition method,[6] and techniques based on the geometrical theory of diffraction.[7,8] Conceptually, the bias methods are largely empirical (using either computer or wafer experiments), the BL is based on an analytical demonstration that the dominant non-Kirchhoff effect is localized near the bounding perimeter of mask apertures, the DDM has been proposed for commercial OPC software, and the last method makes an approximate treatment of the second-order interaction between edges. We will use a simple two-beam imaging scenario to benchmark these techniques.

Aerial image signatures produced by phase gratings in atten-PSM masks have recently been explored as a methodology for the analysis of three dimensional (3D) topography effects;[9] an advantage of these signatures is that they provide a direct way of distinguishing errors in phase and amplitude. In a TMA model, the zeroth order transmitted by an attenuated phase grating will vanish when the ratio of space to line equals the square root of the absorber transmission. Non-TMA effects introduce residual zeroth order transmission, producing a focus-dependent asymmetry between adjacent peaks in the nominally two-beam interference image. The ratio of the asymmetry (difference) between adjacent peaks

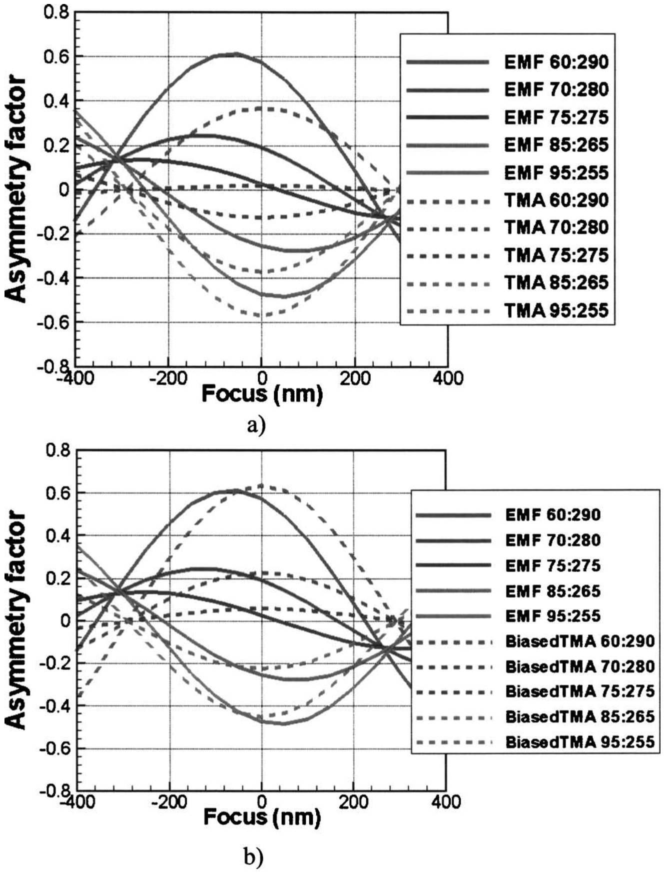


FIG. 4. Aerial image asymmetry factor behavior through focus produced by atten-phase shift 350 nm pitch gratings of different space/line ratios that are illuminated by unpolarized light, as modeled using rigorous electromagnetic simulations (solid curves), as well as (dotted curves) either (a) TMA or (b) biased TMA.

compared to their average (the so-called asymmetry factor[9]) exhibits a characteristic signature through focus, e.g., Fig. 4. Quadratic response through focus (curve bow at the focus origin) indicates unbalanced transmission error, while linear response (curve tilt at the origin) indicates phase error. The dashed curves in Fig. 4(a) are calculated with a TMA simulation; this cannot model either the transmission loss or the phase error, as may be seen by comparison with the solid curves from rigorous emf. Results for the simple isotropic bias approach are shown in Fig. 4(b). A simple isotropic CD bias can compensate for amplitude errors with nearly no runtime penalty relative to TMA, but it contains no phase information and therefore cannot accurately model the response through focus.

The boundary layers[5] (BL) method consists of placing along each mask edge (in simulation) an additional strip feature of fixed width and complex transmission; this BL is designed to mimic emf effects during TMA simulations (the BL being essentially equivalent to the non-TMA fields at the scale of the lens resolution). A key emf effect in atten-PSM is the distortion in the zeroth order by electromagnetic scattering from mask edges, and the width of the BL controls the variations in peak amplitude while the imaginary transmission corrects for phase deviations due to the 3D topography.

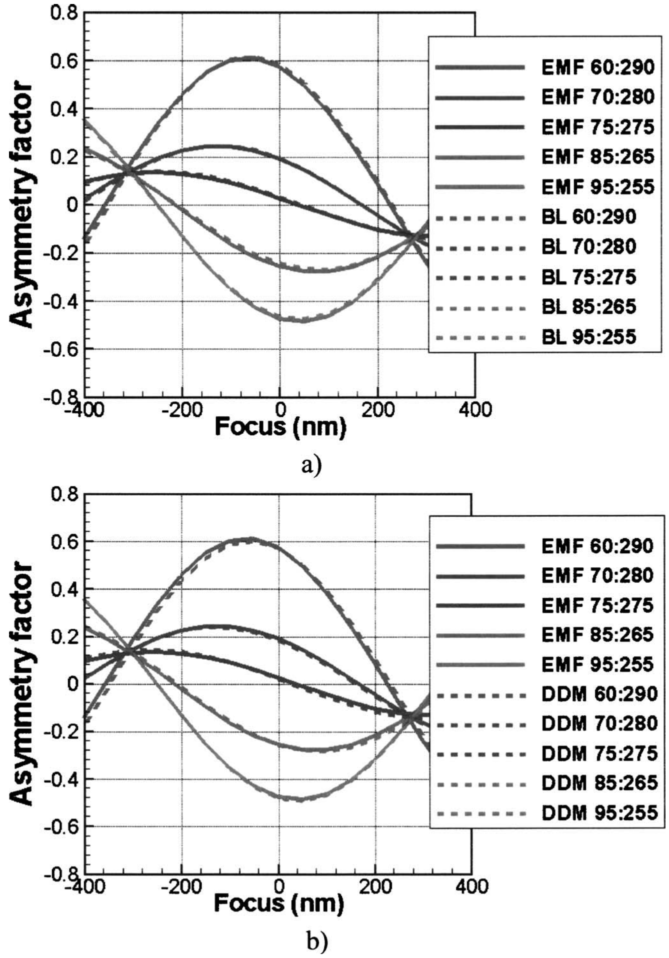


FIG. 5. Aerial image asymmetry factor behavior through focus of Fig. 4 gratings, as calculated with rigorous electromagnetic simulations (solid curves), and with (a) the combination (dotted curves) of two aerial image simulations produced by the BL model of TE and TM polarized illuminations, and (b) by the combination (dotted curves) of two aerial image simulations produced by the DDM model of TE and TM polarized illuminations.

In the classic BL, different sets of parameters are needed for each orthogonal polarization component, with an incoherent superposition providing the aerial image for unpolarized light and thus incurring in a minimum of 2× runtime penalty. The width and transmission coefficients of the BL depend on the edge orientation relative to polarization. These parameters can be deduced through rigorous emf simulation of the mask[5,10] (with associated requirement of a thorough characterization of the mask profile and film stack), or through calibration with resist CD data.[11] As shown in Fig. 5(a), TMA simulations using a boundary layer are capable of capturing the mask emf behavior through focus for different mask space sizes.

In many cases it is possible to improve the computational efficiency of the BL by a factor of 2 or more. While it is not rigorously correct to average coherent terms, one can show that the perturbation induced in the order amplitudes by weak TE and TM boundary fields will only affect the intensity as an average (in lowest order). Thus, an *isotropic* BL, obtained through a (weighted) average of the individual polarization dependent BL's, can provide reasonable numerical accuracy using only a single perturbed mask. The imaging differences between TE and TM are taken into account in the TMA terms and can be included in the perturbation term as a weighted average. For simulation purposes it is possible to fold both polarizations into a single set of imaging kernels,[12] so the isotropic BL allows reasonable numerical accuracy from a single aerial image simulation.

Finally, we consider the so-called domain decomposition method (DDM) proposed by Adam *et al.*[6] and currently implemented in the Calibre simulation platform.[13] In DDM the non-TMA electromagnetic fields are calculated beforehand for scattering by isolated edges; these specific fields are then taken as approximately suitable for representing emf effects at each mask edge in the dense layout. Two separate simulations, one per polarization component, are required to obtain the aerial image under unpolarized illumination, and thus two edge field calculations are required per edge type and a minimum of $2\times$ the runtime. Since this methodology is based on simulation, a thorough characterization of the mask profile and optical parameters is necessary. Figure 5(b) shows that the mask field simulations provided by DDM contain both amplitude and phase information, and are therefore capable of accurately modeling mask emf response through focus.

IV. CONCLUSIONS

In this article we showed that while mask emf effects have the potential to significantly degrade CD uniformity, a simple bias applied during OPC simulations is capable of modeling amplitude errors in the aerial image with reasonable accuracy for lines as small as 30 nm $(1\times)$ and spaces as small as 60 nm $(1\times)$. A simple bias cannot account for phase errors, but we showed that two alternative modeling approaches, the boundary layer and domain decomposition methods, can model phase deviations accurately. We noted that the implementation of either of these two advanced techniques incurs a $2\times$ runtime penalty, but we described an approximation approach that can potentially eliminate the penalty.

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