Self-Aligned-Gate GaN-HEMTs with Heavily-Doped n^+-GaN Ohmic Contacts to 2DEG

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Abstract

We report record DC and RF performance obtained in deeply-scaled self-aligned-gate GaN-HEMTs with heavily-doped n^+-GaN ohmic contacts to two-dimensional electron-gas (2DEG). High density-of-states of three-dimensional (3D) n^+-GaN source near the gate mitigates ñsource-starvation,ò resulting in a dramatic increase in a maximum drain current (I_{dmax}) and a transconductance (g_{m}). 20-nm-gate D-mode HEMTs with a 40-nm gate-source (and gate-drain) distance exhibited a record-low R_{on} of 0.23 Ω·mm, a record-high I_{dmax} of >4 A/mm, and a broad g_{m} curve of >1 S/mm over a wide range of I_{ds} from 0.5 to 3.5 A/mm. Furthermore, 20-nm-gate E-mode HEMTs with an increased L_{sw} of 70 nm demonstrated a simultaneous $f_{\mathrm{T}}/f_{\mathrm{max}}$ of 342/518 GHz with an off-state breakdown voltage of 14V.

Introduction

Deeply-scaled E/D-mode GaN-HEMTs with an unprecedented combination of high-frequency and high-breakdown characteristics offer practical advantages in circuit applications such as sub-millimeter-wave power amplifiers, ultra-linear mixers, and increased output power digital-to-analog converters. During the last few years, through innovative device scaling technologies GaN-HEMT cutoff frequencies have been significantly increased - almost doubled - while maintaining Johnson figure of merit (*JFoM*) breakdown performance [1]. It is reported that in deeply-scaled FETs highly-doped source/drain (S/D) can significantly improve device performance by enhancing electron supply in the source [2,3]. Regrown n^+-GaN ohmic contacts have been shown to be one of viable technologies to reduce parasitic access resistances [4,5]. However, much attention has not been paid to an important role of heavily-doped S/D contacts in mitigating ñsource-starvationò which limits present GaN-HEMT performance. In this paper, we, for the first time, have developed self-aligned-gate GaN-HEMTs with regrown n^+-GaN S/D in direct contact with the 2DEG near the gate, and demonstrate dramatically enhanced DC and RF characteristics in conjunction with engineering of the lateral device dimensions.

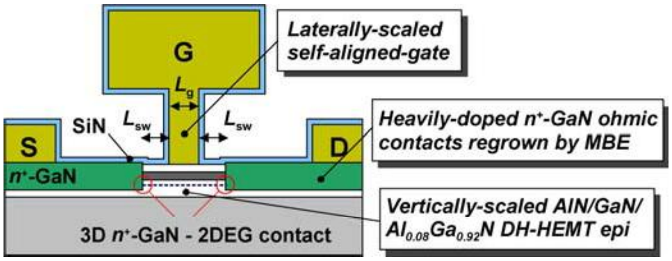
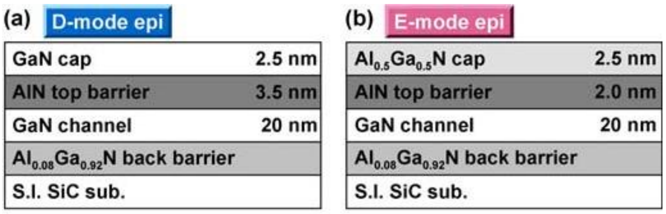


Fig. 1. Deeply-scaled self-aligned-gate double-heterojunction (DH) HEMT with heavily-doped regrown n^+-GaN ohmic contacts to the 2DEG in the GaN channel.



(a) D-mode epi

GaN cap	2.5 nm
AlN top barrier	3.5 nm
GaN channel	20 nm
$Al_{0.08}Ga_{0.92}N$ back barrier	
S.I. SiC sub.	

(b) E-mode epi

$Al_{0.5}Ga_{0.5}N$ cap	2.5 nm
AlN top barrier	2.0 nm
GaN channel	20 nm
$Al_{0.08}Ga_{0.92}N$ back barrier	
S.I. SiC sub.	

Fig. 2. Vertically-scaled (a) D-mode and (b) E-mode DH-HEMT epitaxial structures.

Device design

Fig. 1 illustrates a technology cross-section featuring (i) a laterally-scaled self-aligned-gate, (ii) vertically-scaled depletion and enhancement-mode AlN/GaN/AlGaN double-heterojunction (DH) HEMT epitaxial structures as detailed in Fig. 2, and (iii) heavily-doped n^+-GaN ohmic contacts regrown by MBE. A high 2DEG density (n_{s}) of $1.2(\mathrm{D})/1.1(\mathrm{E})\times10^{13}\ \mathrm{cm}^{-2}$ and a high electron mobility (μ) of 1200(D)/1250(E) $\mathrm{cm}^2/\mathrm{V{\cdot}s}$ were measured after surface passivation with SiN. Heavily-Si-doped n^+-GaN ohmic layers ($7\times10^{19}\ \mathrm{cm}^{-3}$, 50 nm) laterally contact to 2DEG in the GaN channel. A Pt/Au gate is then self-aligned to the n^+-GaN ohmic contacts using a dielectric sidewall process by which gate-source and gate-drain distances are determined by the sidewall thickness (L_{sw}). Fig. 3 compares two regrown n^+-GaN ohmic structures; (a) A regrown n^+-GaN ohmic layer directly contacts to the 2DEG, where electrons are supplied from the 3D n^+-GaN source to the 2DEG channel near the gate (3D-2D). (b) An n^+-GaN ohmic layer was regrown on top of the (Al)GaN/AlN barrier layers as reported in our previous paper [1], where electron are

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **MAR 2013**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE
Self-Aligned-Gate GaN-HEMTs with Heavily-Doped n+-GaN Ohmic Contacts to 2DEG

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
HRL Laboratories, LLC, 3100 Malibu Canyon Road, Malibu, CA 90265-4797, USA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADB387878. GOMACTech -13 Government Microcircuit Applications and Critical Technology Conference (38th) on Microelectronics for Net-Enabled and Cyber Transformational Technologies. Held in Las Vegas, Nevada on 11-14 March 2013

14. ABSTRACT
We report record DC and RF performance obtained in deeply-scaled self-aligned-gate GaN-HEMTs with heavilydoped n+-GaN ohmic contacts to two-dimensional electrongas (2DEG). High density-of-states of three-dimensional (3D) n+-GaN source near the gate mitigates source-starvation, resulting in a dramatic increase in a maximum drain current (Idmax) and a transconductance (gm). 20-nm-gate D-mode HEMTs with a 40-nm gate-source (and gate-drain) distance exhibited a record-low Ron of 0.23 ·mm, a record-high Idmax of >4 A/mm, and a broad gm curve of >1 S/mm over a wide range of Ids from 0.5 to 3.5 A/mm. Furthermore, 20-nm-gate E-mode HEMTs with an increased Lsw of 70 nm demonstrated a simultaneous fT/fmax of 342/518 GHz with an off-state breakdown voltage of 14V.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

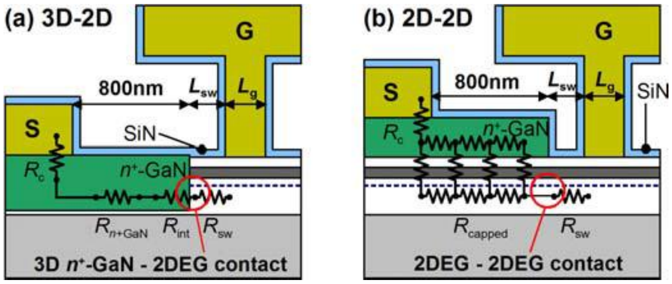


Fig. 3. Comparison of two regrown n^+-GaN ohmic structures; (a) a new 3D n^+-GaN source to 2DEG channel contact (3D-2D), and (b) 2DEG source to 2DEG channel contact (2D-2D) in our previous paper [1].

supplied from the 2DEG source to the 2DEG channel (2D-2D).

Results and Discussion

An access resistance (R_{ac}), defined as a total resistance from the ohmic metal to the edge of the gate, of 0.101 $\Omega\cdot$mm is the lowest value ever reported in GaN-HEMTs (Fig. 4). Resistance components of R_{ac} are shown in Fig. 4, which were extracted from a TLM test structure, contactless sheet resistance measurement, and dependence of device on-resistance (R_{on}) on L_g (Fig. 5). The regrown interface resistance (R_{int}) between the n^+-GaN and the 2DEG is only 0.026 $\Omega\cdot$mm, reaching its theoretical limit [$\sim h/(2q^2\cdot n_s^{1/2})$ = 0.036 $\Omega\cdot$mm] [6]. More importantly, this new approach not only reduces R_{ac} but also increases flexibility in a material choice of GaN-HEMT epi structures since the R_{ac} is independent of the barrier materials as is the case for the conventional approach. Fig. 6 and Fig. 7 compare DC characteristics of 60-nm D and E-mode HEMTs with 3D-2D and 2D-2D contacts. Reduced R_{on} by -18% (-19%) for D (E)-mode device is a result of the reduced R_{ac}. I_{dmax} is dramatically increased by +34% (+45%) for D (E)-mode device due to an increase of g_m at high I_{ds}. This result clearly illustrates that typical g_m roll-off at high I_{ds} observed in previous devices is due to the limited electron supply from the source, i.e., ñsource-starvation.ò 20-nm-gate D-mode HEMTs with L_{sw} = 40 nm exhibited a record-low R_{on} of 0.23 $\Omega\cdot$mm, a record-high I_{dmax} of >4 A/mm, and a broad g_m curve of >1 S/mm over a wide range of I_{ds} from 0.5 to 3.5 A/mm (Fig. 8). Fig. 9 shows a peak g_m of E-mode HEMTs as a function of L_g for various L_{sw}, indicating that the closer the n^+-GaN/2DEG interface is to the gate, the more efficiently electron are supplied from the 3D n^+-GaN source. The record-high g_m of 2.2 S/mm was measured for a device with L_g/L_{sw} = 40/50 nm.

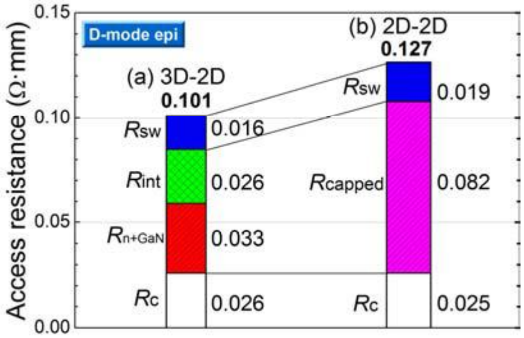


Fig. 4. Access resistance (R_{ac}) components for two regrown n^+-GaN ohmic structures shown in Fig. 3. An extremely small R_{ac} of the new 3D-2D structure resulted from ideal regrown interface resistance (R_{int}) that reaches the theoretical limit.

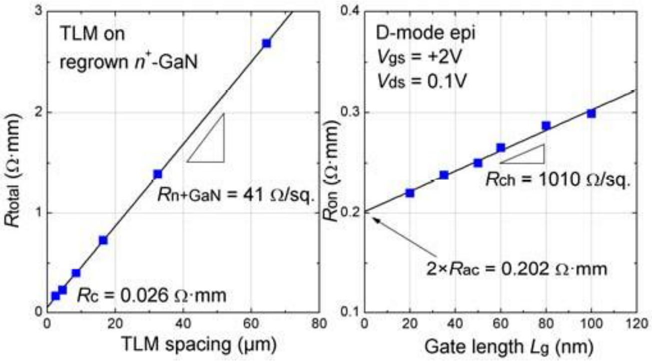


Fig. 5. Extraction of access resistance (R_{ac}) components shown in Fig. 4 using a TLM on a regrown n^+-GaN and dependence of R_{on} on L_g.

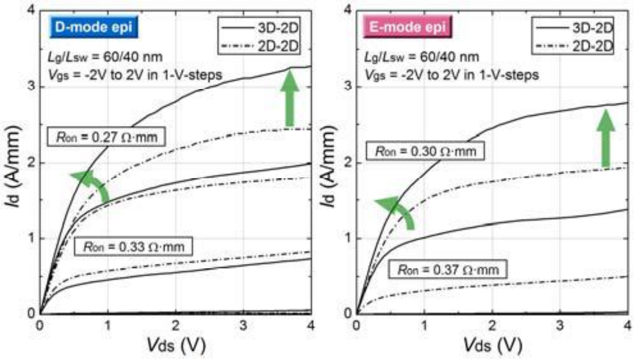


Fig. 6. Output characteristics of 60-nm D and E-mode HEMTs (L_w = 40 nm) with 3D-2D and 2D-2D contacts, demonstrating a reduction of R_{on} and a dramatic increase of I_{dmax} using 3D n^+-GaN source.

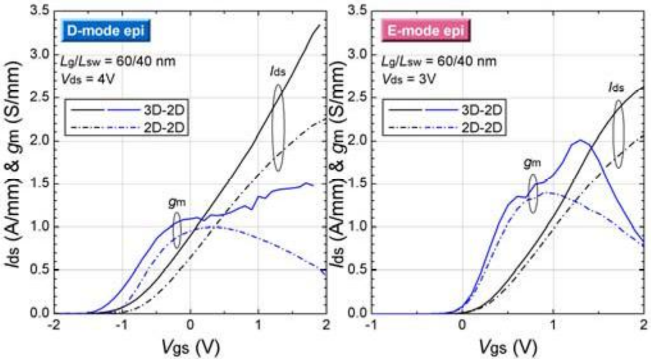


Fig. 7. Transfer characteristics of 60-nm D and E-mode HEMTs (L_w = 40 nm) with 3D-2D and 2D-2D contacts, demonstrating suppressed g_m roll-off at high I_{ds} due to enhanced electron supply by 3D-2D contact.

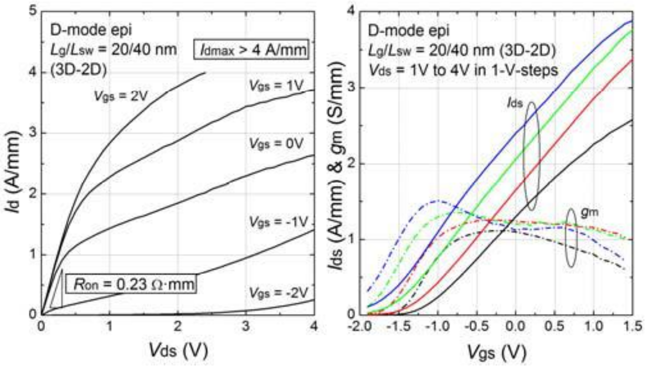


Fig. 8. Output and transfer characteristics of a 20-nm D-mode HEMT (L_{sw} = 40nm) with a 3D-2D contact, showing a record-low R_{on} and a record-high I_{dmax} with very broad g_m curves.

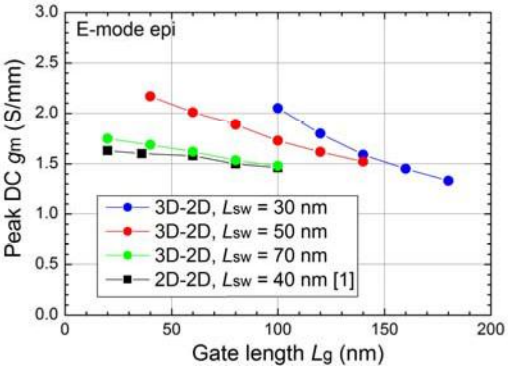


Fig. 9. Peak DC g_m of E-mode HEMTs as a function of L_g for various L_{sw}, indicating enhanced electron supply with reduced L_{sw}.

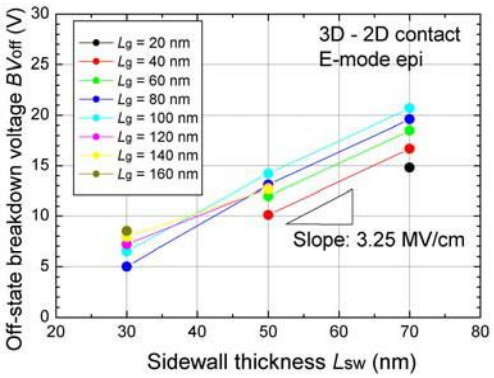


Fig. 10. Off-state breakdown voltage (BV_{off}) of E-mode HEMTs linearly increases with L_{sw} with a slope of 3.25 MV/cm.

While the shorter gate-source distance (L_{gs}) enhances the electron supply, the longer gate-drain distance (L_{gd}) increases breakdown voltage and reduces output conductance (g_d) and gate-drain capacitance (C_{gd}). Off-state breakdown voltage (BV_{off}) increased linearly with increasing L_{sw} with a slope of 3.25 MV/cm, close to the critical field of GaN (~3.4 MV/cm) (Fig. 10). Drain induced barrier lowering (*DIBL*) for sub-50-nm gate lengths (L_g) improved significantly with increasing L_{sw} owing to an increased gate to drain electrostatic isolation (Fig. 11), leading to a lower g_d due to suppression of the ñshort-channel-effect.ò A balanced device design with L_g/L_{sw} = 20/70 nm in the E-mode HEMTs resulted in a simultaneous f_T/f_{max}=342/518GHz with a BV_{off} of 14V. This record-high f_{max} is attributed to the decreased g_d and C_{gd} due to the increased gate-drain distance together with a high g_m enabled by the new 3D n^+-GaN source contact to the 2DEG (Fig. 12). Fig. 13 shows good scaling behavior of f_T/f_{max} with L_g down to 20 nm. As a result of proportional device scaling and enhanced electron supply in self-aligned-gate

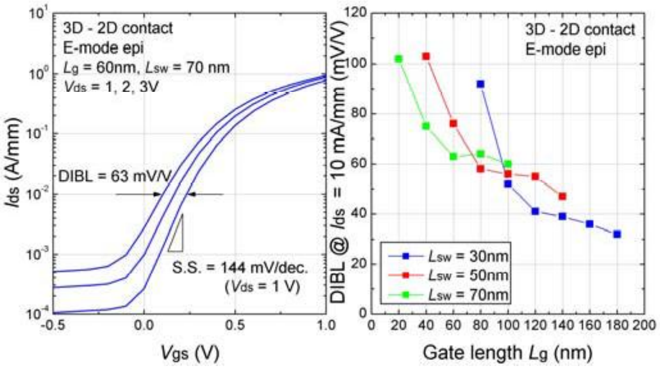


Fig. 11. Sub-threshold characteristics of an E-mode HEMT with L_g/L_{sw} = 60/70 nm. Dependence of *DIBL* on L_g for various L_{sw} shows an improved gate to drain electrostatic isolation with increased L_{sw}.

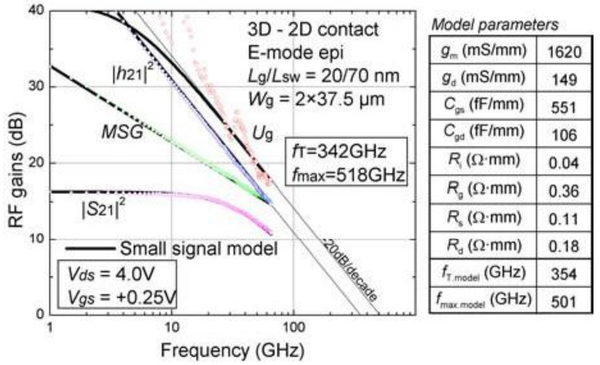


Fig. 12. The best combination of f_T/f_{max}=342/518GHz was achieved in a HEMT with L_g/L_{sw} = 20/70 nm. This record-high f_{max} is attributed to a reduced g_d and C_{gd} while maintaining a high g_m.

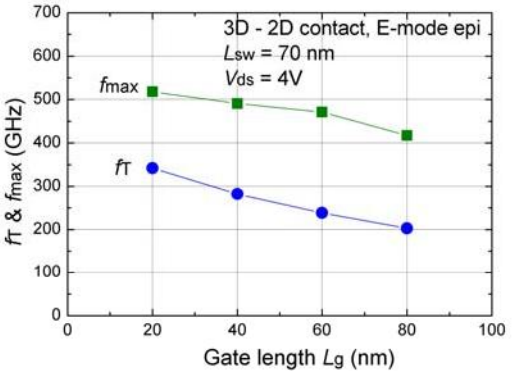


Fig. 13. Peak f_T/f_{max} vs. L_g showing high L_g scalability down to 20 nm.

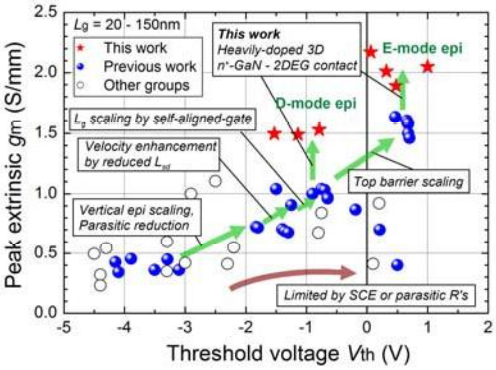


Fig. 14. Comparison of extrinsic peak g_m vs. V_{th} with the state-of-the-art results reported for GaN-HEMT technology.

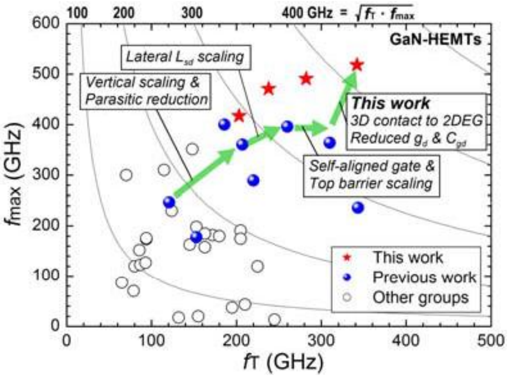


Fig. 15. Proportional device scaling and enhanced electron supply in deeply-scaled self-aligned-gate GaN-HEMTs successfully resulted in a record f_T and f_{max} exceeding an average cutoff frequency of 400 GHz.

GaN-HEMTs, enhanced peak g_m in excess of 2 S/mm (Fig. 14) and an average cutoff frequency [= $(f_T \cdot f_{max})^{1/2}$] of >400GHz were obtained (Fig. 15).

Conclusion

Heavily-doped n^+-GaN S/D contacts to the 2DEG in deeply-scaled self-aligned-gate GaN-HEMTs were demonstrated for the first time. The new technology was shown to effectively mitigate ñsource-starvation,ò resulting in a significant enhancement in R_{on}, I_{dmax}, g_m, and g_m linearity. An R_{on} of 0.23 Ω·mm, an I_{dmax} of >4 A/mm with a broad g_m curve of >1 S/mm over a wide range of V_{gs} was obtained in 20-nm D-mode HEMTs with L_{sw} = 40 nm. In conjunction with lateral device size optimization for a reduced g_d and C_{gd} as well as an increased BV_{off}, a record f_T/f_{max} of 342/518 GHz was obtained in 20-nm HEMTs with a *JFoM* of 4.8 THz·V.

Acknowledgment

This work was sponsored by the Defense Advanced Research Projects Agency (DARPA) Nitride Electronic NeXt-Generation Technology (NEXT) program under Contract No. HR0011-09-C-0126, program manager Dr. John Albrecht. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressly or implied, of the Defense Advanced Research Projects Agency or the U.S. Government.
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