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C K K sK , , K S D K

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In-situ s K K - s , s K , s K s ff s , K s

K , C , W , L ’ *, L H ’ , C , L , L , s W , K s Ess , L L , G , T P s

Gemmological Institute, China University of Geosciences, Wuhan 430074, PR China
Hubei Gem and Jewelry Engineering Technology Research Center, Wuhan 430074, PR China
School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, PR China
Mechanical Engineering, University of Birmingham, Birmingham B15 2TT, UK
School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, PR China
WMG, Materials Engineering Centre, University of Warwick, CV4 7AL Coventry, UK

A R T I C L E I N F O

Keywords:
T - s
C s s ff
S K s K
C s K
E K K K s

A B S T R A C T

C K , K - s (3DG) K w s sK K K ss, sK K K s s w s sK K . H w K s K - sK K K K - s K s K s K (SLM) K K K K - s (3D) s K K. G w s K *in-situ* w s K (CVD) K K s C K K, 3DG s Ks. A K K wK CVD K w K SLM K s ff K Ks K s K 3DG -sK K (K K , sK, K) K -sK K (K K , s K) K K K s s ff . T 3DG/ s ff 88% 27% K K K K (EMI) s K ff s , s K . P K , K sKEMI s ffi- (*SE*) K 47.8 B K2.7 GH K *SE* 32.3 B KK 2–18 GH . T s sK s s K K K SLM s sK K .

1. Introduction

G , s sK sp^2 K s, s w K w K K K s , s s (2630 ^{2} $^{-1}$) 1 , K K s K (2 10^{5} ^{2} V^{-1} s^{-1}) s K K K (5000 W $^{-1}$ K^{-1}) 2 . H w , K sK π-π K K Kv Kv s (2D) s - s K s K - K , s s ff s s sK K s KK sK , s , w , - ss Ks s sK K s s 3 . A K K s K s fi K ff K Ks Kv K K s s K - K s. C K w K K s s, K - s - (3DG) s ws K s sK (99.7%), w s fi K (0.6 $^{-2}$) 4 w K s fi s s s w s K, sK K K ss K s s K K K Kv - s (2DG), K K s K s s 5 , sK 6,7 , s s s 4 , K K K (EMI) s 8 s . V s K s K s 3DG K , 9 , K K 10 , s - ss 11 , - 12 s . H w , K - K K s sK s s. F , K K s ff K s K s s 13 . S - ss K s ss K (s s) w K s s K 14 . D - K s ws KK K K s K s KK s s K K s K ss K K sK 15 . M sK s K sK K K s Ks K K K s , w K K- K CVD K s ws K s s K, s w sK K s - - K 16 . B Ks K , w K K s w , ss K K K s sK K w K s K

* C s K K G I sKK K, C U s K G s s, W 430074, PR C .
E-mail address: @ . . (. L).

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Available online 18 April 2020

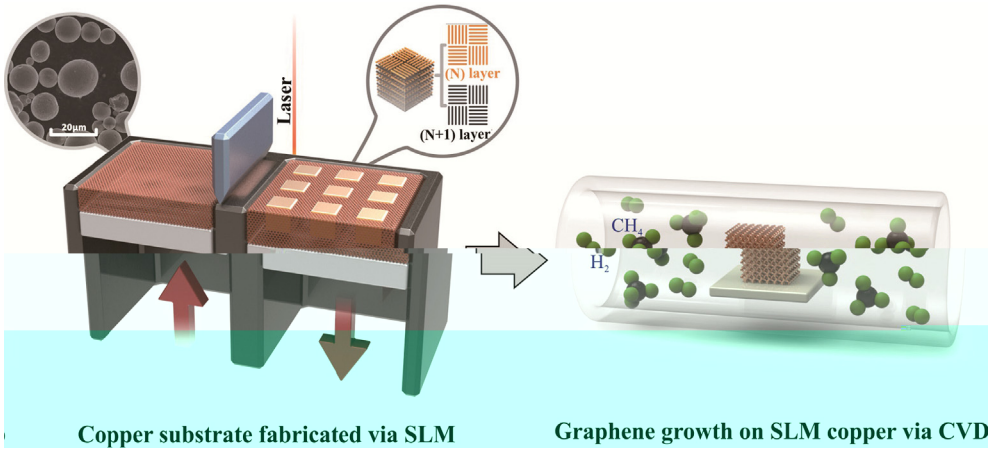

Fig. 1. I sk k 3DG/C s sk k , k ss: s ff , k SLM (k, *in-situ* , wk k s ff , CVD (k. (F k kk k s k k s fi , k , s k k w s k s k .)

ASTMB193-2002 kw k, s s 2 2 20 ^{3} k k, k kk s. T k ff s k , s k k (2 10 10 ^{3}) s sk k (5 10 10 ^{3}) w ASTME1461-2013 w k, s s k, k kv kk s s k LFA (L s fl s k , N Kis LFA457, G). R s k s (SENTERRA, B , G) w s s k , k k 3DG/C s ff w k , - kk w k 514 . T *S* , k s (*S11* , *S21*) w s w k k kv , (VNA, A KPNA-N5244A, US) s k , k 2–18 GH . T s SE_{kk}, *SE* s k , *SE* fl k w k , s E . 2–5 k S k I k .

3. Results and discussion

3.1. Formation of SLM copper

3.1.1. SLM manufacturing of copper under different line energy densities

T sk ff k s (s w s s) w sk k s k . D ff k s k k s w s , k ss w w k sk s s (F . 2) s k k , 30% w s k (A), 26.7% sk (B), 16.7% k sk (C) 26.7% ss k (D). D ff k s s k s s k, LED (J/) 27 (E . 6, s k SI). T s k s ss k k k k s fl k k , k k . T ss k s k s , k k ffi k w k k ss k s. I A, s k w s ffi kk s k s k w s s ffi k I B, k w k sk w k k s w k k k w sk k k s w k fi . T kfl w k k s sk w k s ffi k k k k k k , s s k , k s k k w s k w k kLED 400 J/ (C). W ss LED (> 800 J/) s , 130 μ w k - s s (D), w w s - s sk ss s s k k ss k k ss k w k k w s w s w s s 28 .

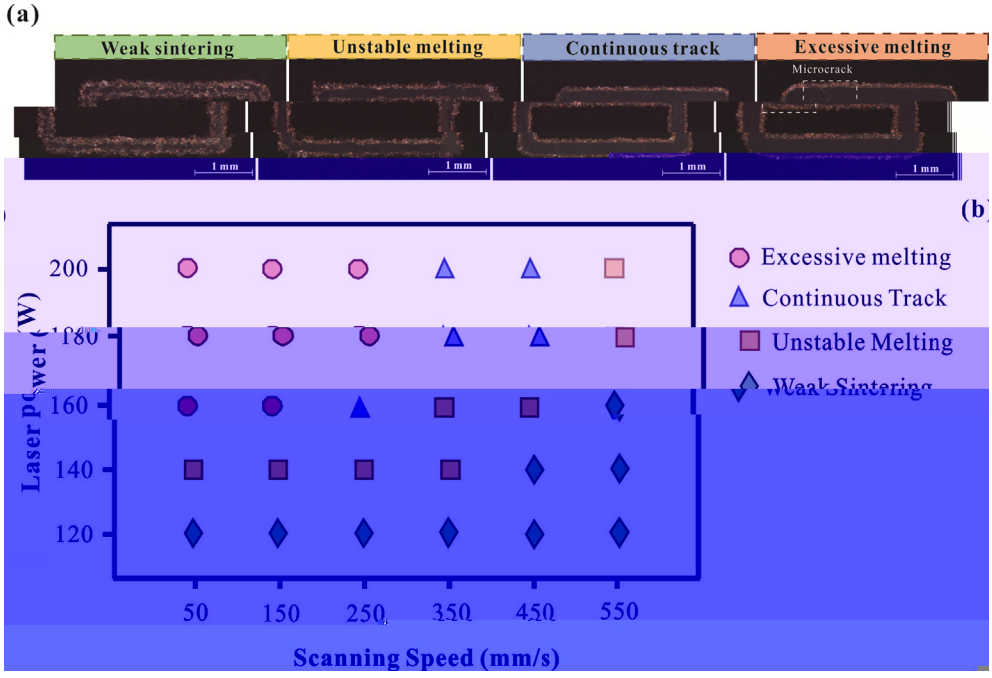

Fig. 2. ( ) T k s w s k , sk k , - k s k , , ss k , s k ; ( ) ss w w s w s s . (F k - kk k s k k s fi , k s k k w s k s k .)

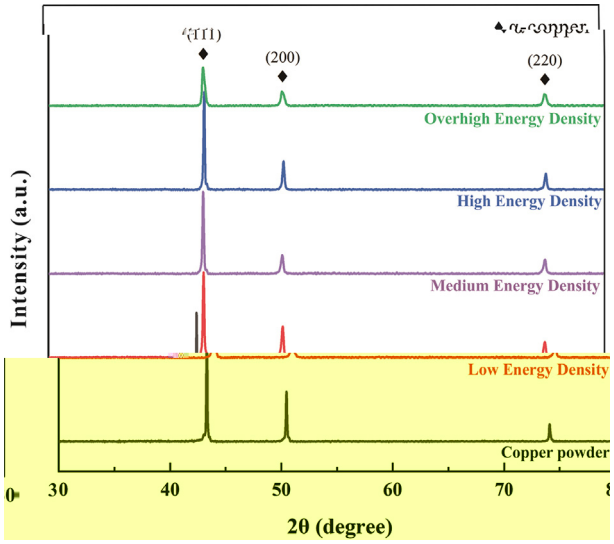

Fig. 3. RD [illegible] s [illegible] s [illegible] w [illegible] s- [illegible] s - s. (F [illegible] [illegible] [illegible] s [illegible] [illegible] s fi , [illegible] s [illegible] [illegible] w s [illegible] s [illegible] .)

3.1.2. Formation of anisotropic microstructure under different volumetric energy density

T s α- [illegible] RD [illegible] s [illegible] (1 1 1) (2 0 0) fl [illegible] s ff [illegible] [illegible]2θ = 43.32 2θ = 50.45 , s [illegible] (F . 3), [illegible] (1 1 1) [illegible] w s . T s- [illegible] s s s [illegible] s RD [illegible] s [illegible] [illegible] s [illegible] [illegible] w [illegible] s [illegible] s ff s [illegible] [illegible] s w fi [illegible] [illegible] SLM ss. I [illegible] , [illegible] ff [illegible] s SLM s s s [illegible] [illegible] ff [illegible] s, [illegible] [illegible] s s [illegible] ss [illegible] s- [illegible]s s [illegible] [illegible] [illegible] 29 . T [illegible] [illegible] w s [illegible] [illegible] - [illegible] s [illegible] [illegible] SLM [illegible] [illegible] s s s s w [illegible] [illegible]T [illegible] s [illegible] w

s : ( ) [illegible] - s, ( ) - [illegible] w , ( ) s s. A[illegible] ss [illegible] 3000 J/ ^{3} (F . 4**a**), [illegible] [illegible] w s s w s 180 μ , s [illegible] s w [illegible] [illegible] w (F . 4**d**). T [illegible]s [illegible][illegible] s s [illegible] [illegible] M [illegible] 30 s [illegible] fl [illegible] [illegible] [illegible] [illegible] [illegible] . T s s [illegible][illegible] s [illegible] [illegible] - s s w [illegible] w s ss fi [illegible] s s [illegible] [illegible]W [illegible] [illegible] [illegible] [illegible] s s [illegible] [illegible] 857 J/ ^{3}, s [illegible] w [illegible] w s s w [illegible] [illegible] [illegible] s s s [illegible] [illegible] w s (F . 4**b**). U [illegible] s [illegible] s, [illegible] [illegible] s fi- [illegible] [illegible] 96.2% w [illegible] [illegible] . H w , w [illegible] s [illegible] [illegible] [illegible] s[illegible] , s - [illegible] w s s [illegible] s. T [illegible] [illegible] [illegible] [illegible] s [illegible][illegible] s[illegible][illegible] [illegible] s [illegible] [illegible] [illegible] [illegible] [illegible] (398 W $^{-1}$ K^{-1}), [illegible] s s ffi [illegible] [illegible] w s [illegible] [illegible][illegible] w [illegible] s [illegible] (F . 4**c**). G s s s [illegible] s s , w [illegible] s [illegible] [illegible] w [illegible] [illegible] M - [illegible] . B s s, [illegible] [illegible] [illegible] s s [illegible] [illegible] [illegible] w [illegible] s s [illegible] s s [illegible] s [illegible] s [illegible] s s [illegible]s [illegible] [illegible] SLM ss 31 . I [illegible] s[illegible] [illegible] w [illegible] 128 J/ ^{3}, [illegible] - [illegible] w s ss [illegible] w s w [illegible] w-s w fis s - s, [illegible] 88.6% [illegible] - [illegible] s [illegible] (F . 4**d**).

T [illegible] s[illegible] [illegible] s [illegible] SLM ss w s w [illegible] s[illegible] [illegible] [illegible] s (F . 5). T [illegible] [illegible] - s [illegible] [illegible] w [illegible] - [illegible] s [illegible] , w w [illegible][illegible] [illegible] [illegible] [illegible] s [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] T [illegible] [illegible] [illegible] [illegible] [illegible][illegible] s – [illegible] s [illegible] [illegible] [illegible] [illegible] [illegible][illegible] [illegible][illegible] w [illegible][illegible] [illegible] w w s [illegible] [illegible] [illegible] [illegible] [illegible] s s[illegible] [illegible], w [illegible][illegible]s [illegible] w[illegible] - s[illegible] [illegible] s 32 . T [illegible] [illegible] [illegible] [illegible] s s[illegible][illegible] [illegible] s fi s [illegible] [illegible]fl w [illegible] - [illegible] . S [illegible] [illegible] w W [illegible] . 33 , [illegible] [illegible] [illegible]s[illegible] [illegible] [illegible] [illegible] , s [illegible]

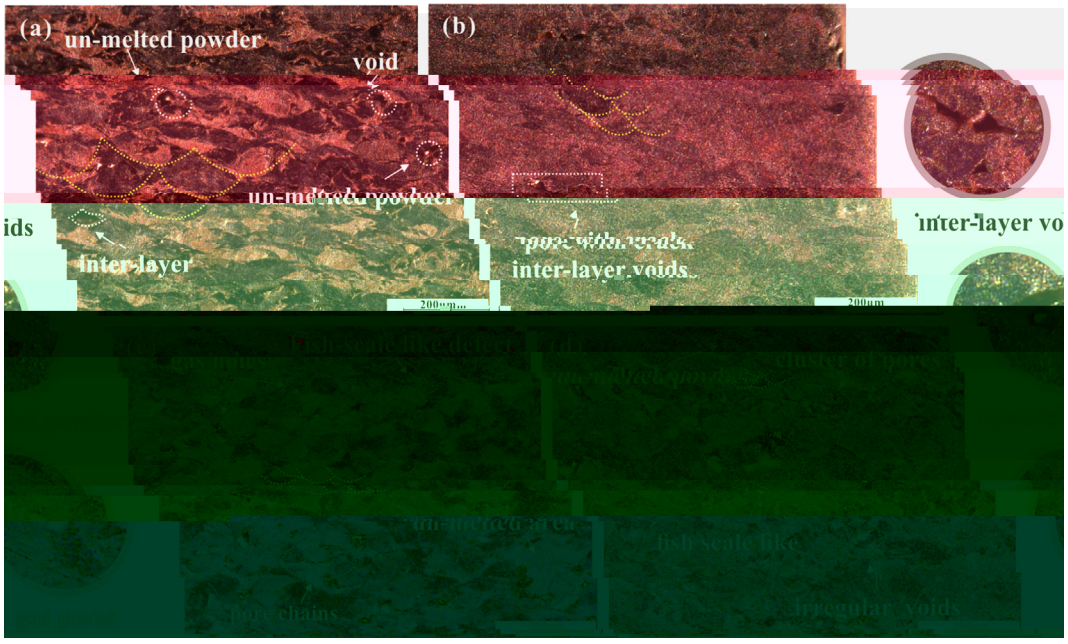

Fig. 4. O [illegible] s [illegible] s s [illegible] s [illegible] [illegible] [illegible] : ( ) ss (3000 J/ ^{3}), ( ) (857 J/ ^{3}), ( ) (285 J/ ^{3}), ( ) w (128 J/ ^{3}), s [illegible] . (F [illegible] [illegible][illegible] [illegible] s[illegible] [illegible] s fi , [illegible] s [illegible][illegible] w s [illegible] s [illegible] .)

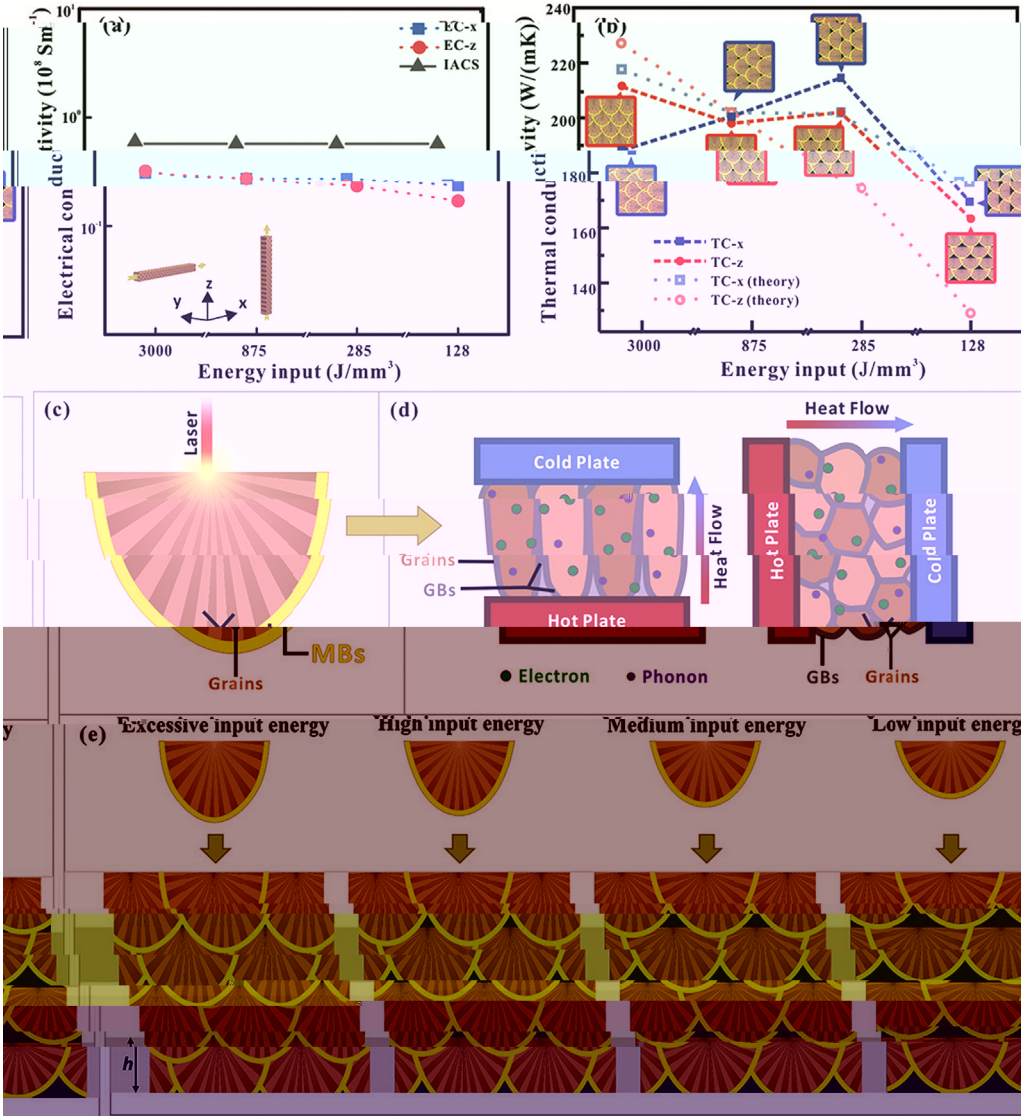

Fig. 7. ( ) E ( ) s ; ( ) s ; ( ) s . (E s). (F s fi , s w s .)

s s s s .

3.3. Morphology and structure of CVD 3DG/Cu porous scaffolds

F s s ff s w ff s w s ss s s ff . G w s *in-situ* w CVD . As w s s ff s s, s s s , w v s fi s 39 . A s , - s w w s s w 33 V , s (25 V) 39 . Us s w C N , L . 40 s - w ss. H w , s s s s (. s 23 , - s s 41) w CVD- w s s fl w s w . A , w s s SEM, w ss-s - . T SEM - s 3DG/C s s ff - w w s 450 μ (F . 8**a**). A fi s (F . 8**b**), fl s w s s s ff , s . T - s s s ff s s, EDS s s ss w s (F . 8**c-d**), w fi s s s s . A fl w s s fi (F . 8**e-g**). T 3DG/C s s ff s w - w s w s s s s (F . 8**h**). R s s w s 3DG/C - s s . T G- (~ 1590 $^{-1}$) s w s 2D- (2699 $^{-1}$) s s w ss s s w s 42 (F . 8). S D- (~1350 $^{-1}$) fl s - 43 , s s D G s (I_D/I_G) w s

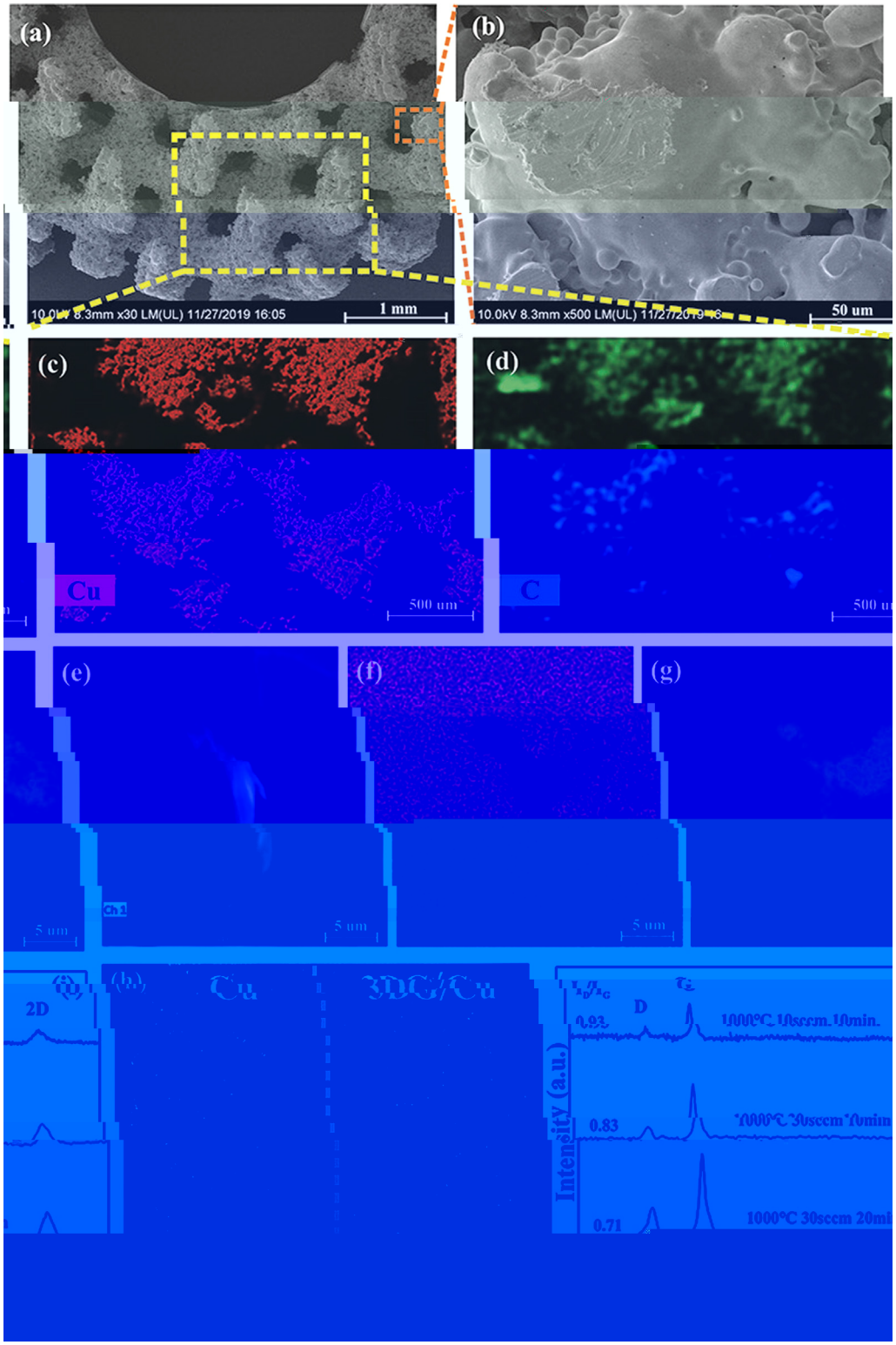

Fig. 8. (-) SEM s 3DG/C s s ff ff fi s; EDS ( ) C ( ) C; ( ) fi SEM , s EDS ( ) C ( ) C; ( ) s wK OM; ( ) R s s ff ff K wK K s. (F K KK K s K s fi , K s K K w s K s K .)

K s K K. W K s K wK K s w fl w Ks, K I_D/I_G s 0.71 K 0.93, K - s K KK K K K K s K sK K s. As s , K wK K (wK T ff s s sK K s K K K 1000 C, fl w K CH_4 30 s , wK K K C s s ff , K 26.8% s 20) w s s K 3DG/C s sK K .

3.4. Thermal property and EMI shielding effectiveness of 3DG/Cu porous scaffolds

K K K s, K 14.8% s

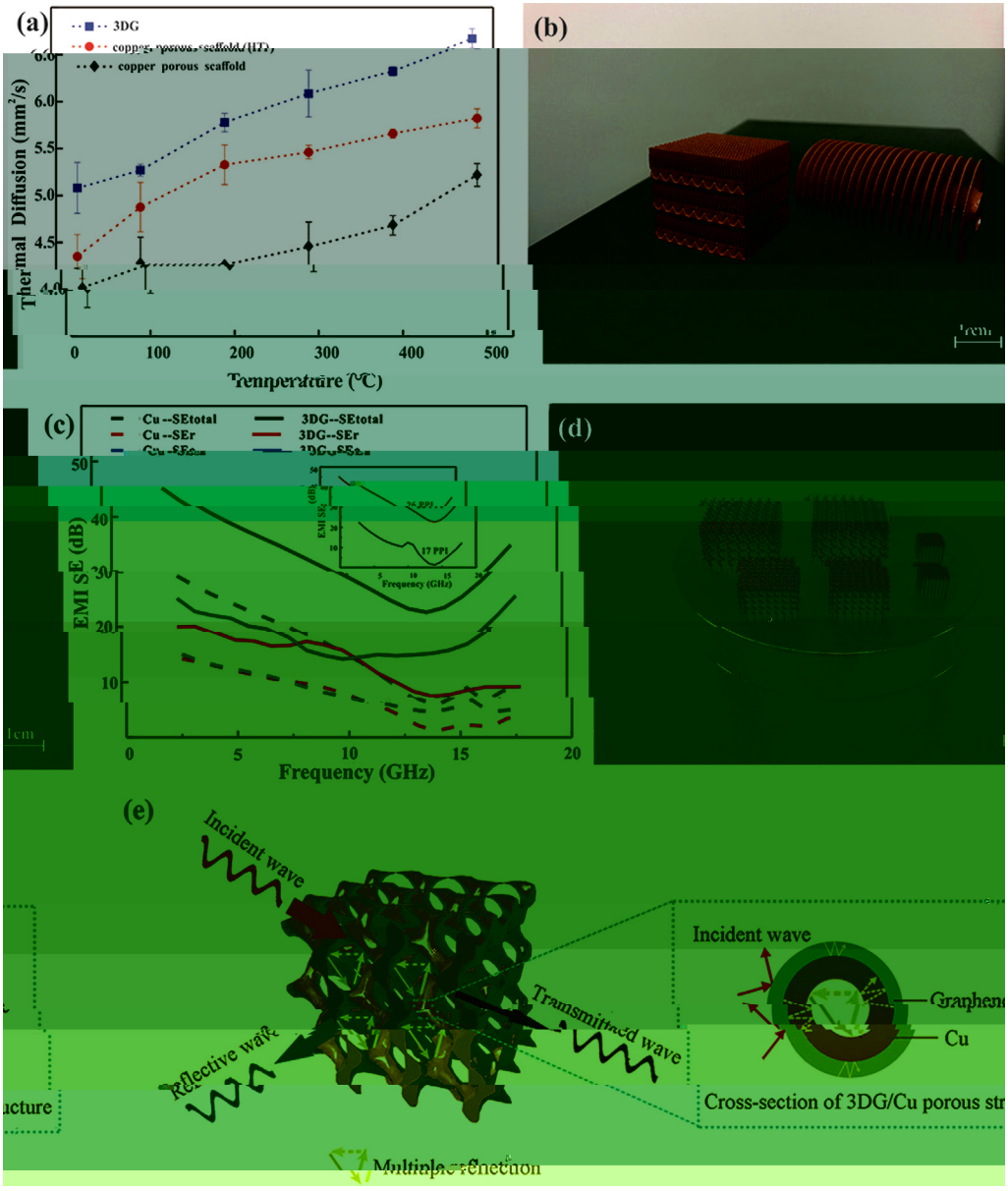

Fig. 9. P 3DG/C s s ff : ( ) ff s ; ( ) SLM - ssfl w (w -s fl) -PPMA, sPS. ( ) EMI SE; ( ) C s ff w ff s ; ( ) S 3DG/C EMI. (F s fi , s w s .)

Table 1
C s - s s s w s s sPS EMI s - -PPMA, sPS.

Coating materials	Substrate	Method	Maximum shielding efficiency (dB)	Improvement of thermal property (%)	Ref
G s	G	I s + + + s	37	–	50
G	PS	H - ss ss + s	29.3	–	56
G	PMMA	S + + +	19	–	57
C /G /C	A	S fi +	–	8.5	58
G	N	F + CVD	–	554	59
G	C -N	E ss +	20	–	60
G	C	P w s + CVD	–	2.4	61
G s	C	F - +	47	6.3	62
G	C	CVD + SLM	47.8	27	T s w

Note: ( )-PPMA, sPS.

HT s s s s
in-situ w (F . 9**a**). S s - -
s s s
3DG/C s s ff ss ss s -
. I s s w HT s s
s s w
1–2 s I s s ,
s s s w s
w , s s s . W
s , s SLM
– ssfl w (w fl
ss 500 μ) -
s w s ss
(F . 9**b**), s
s w s
s -s . G s s s -
s s, s s, s ,
w s
(T 1). I s w s
s w s s s. O -
s s s w
s , N .

T s 3DG/C s s ff
EMI, EMI *SE,* w s
(EM) , w s
2–18 GH (F . 9**c**), s
. W *in-situ* w
s s ff , *SE* s 15.9 32.3 B, w
47.8 B (88.2% s), s ss -
20 B. T
s 3DG/C fi
s s. J K . 44 EMI
s s s w s s. T EMI *SE*
133% w s s
(., s s) 20 110 PPI (s).
R K s 45 s w s s s
s s EMI
. W s s s s s
17 26 PPI (F . 9**c** **insert**) 105%
EMI *SE*. I w s, EMI s s s
s ff s w s
SLM. T
3DG/C s s 26 PPI EMI *SE*
32.3 B, s 99.9% EMI w s. T s
s w s s 60
(30 s s s ff) 46 . T EMI
s s 3DG/C w s - s -
s s s T s 1. I EMI *SE*
3DG/C w s s s
3D - s s s,
s
T s s EMI s fl (SE_r), s
(SE_a) fl s (EM) w s 47 ,
w w s,
s, s s s, s
48 . R s s 49 w
, s fl
w s, w s w s s.
T s s w s EMI w
ss s fi
s 50 . R s s EMI
s . T s s s - -
s w w - s
w fi s, s s C 51 . F
s - s , w s -
52 S O_2 53 . W s
3DG/C s s ff s w s fi s
SE$_r$ *SE*$_a$, s s s w F . 9**e**. W w s
w s 3DG/C s s ff , s
w s w fl w s
w s s s s ff . S -
s , s 3DG/C s s
s s fl s s s
w s w s s w EM w
EM w s fi s w w
s w EM w s, s
ss *SE*$_r$. O
, s s
s ff , w w s fi EM
w s s ff , s s EM -
s ss s s s. T
s s ff s w
w J 54 . I s w fi s w s
fl ff . M , s
s s s s
s s, s s s
w s s, fl s s
EM w s s , s s ss
EM w s. T s w s
w s 44 . T s s ss s
s w 3D s s
s s s s EM w s w s
s. I s , s CVD s
R s s s s -
s s S 3.3 s s s s
s s ss s , s
s 55 . I s
EM w s w s s s, w s
s s s s ss. O w , s
s s 3DG/C s s fl s , s , s s fi
s s . T s s s
s w s s s ff s
s s s .

4. Conclusions

A 3DG/C s s ff w s ss w
s *in-situ* s CVD .
T s s s s w
s ss ff . W s
s s s , 3DG/C
s s s EMI *SE*
15.9 (s) 32.3 B,
47.8 B (88.2% s), s w s 26.8% s
ff s . T 3DG/C s s
ff fl s, s fl s -
s s. T s EMI
3DG/C s s ff s s
s EMI s

Credit authorship contribution statement

Kaka Cheng: C , M , F s, W - **Wei Xiong:** V , I s , W - **Yan Li:** W - w & , F s , R s, S s . **Liang Hao:** F s . **Chunze Yan:** R s, F s . **Zhaoqing Li:** V . **Zhufeng Liu:** F s s. **Yushen Wang:** I s , S . **Khamis Essa:** W - w & . **Li Lee:** D . **Xin Gong:** S . **Ton Peijs:** W - w & , S s .

Declaration of Competing Interest

T s fl s .

Acknowledgement

T w fi s N N S F C (N . 51671091, N . 51902295, N . 51675496). T s s F R s F s C U s G s s (W) (N . (N . CUG170677) H P N S F (N . 2019 CFB264).

Appendix A. Supplementary data

S s:// . /10.1016/ . s .2020.105904.

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