Electronic Supplementary Information:

Progress of alternative sintering approaches of inkjet-printed metal inks and their application for manufacturing of flexible electronics

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ESI Table 1 Summary of chemical sintering approaches.

Metal ink	Sintering agent / ink	Substrate	Reaction conditions	Performance	Ref
Custom Ag NP ink (dodecylamine stabilizer)	Methanol, ethanol, *iso*-propanol, water	Glass	Immersing for 10 to 7200 s 40 to 60 °C	Methanol: 2.3×10^{-5} Ω m Ethanol: 7.3×10^{-4} Ω m *Iso*-propanol: 7.9×10^{-2} Ω m Water: not conductive	[1, 2]
Custom Au NP ink (thiol stabilizer)	NO_2 vapor	Glass	50 min at room temperature	Not specified	[3]
Custom Ag NP ink (PAA stabilizer)	PDAC (cationic polymer) 0.1wt% solution	Glass, PET, paper	Room temperature (time not specified)	20% of bulk Ag conductivity	[4]
Ag NP ink (ANP DGP-	Silanol groups on the	Different	Room temperature, varying	27% bulk Ag conductivity at 85%	[5, 6]

45LT-15C) with PVP stabilizer	paper surface	papers	humidity (1 to 85%) before and after printing, exposure for one day	humidity	
Custom Ag NP ink	NaCl (in the ink) or HCl vapor	PET	Room temperature (water evaporation), 10 s exposure time to HCl vapor	NaCl: 10% of bulk Ag HCl: 41% of bulk Ag	[7, 8]
Plated Ag NP layer	$CaCl_2$, $MgCl_2$, HCl, LiCl, NaCl, $MgSO_4$, $FeSO_4$	Glass, silicon, PMMA, PTFE,	Immersing into electrolyte solutions for 10 s at room temperature	0.85 Ω sq^{-1} (HCl), 0.43 Ω sq^{-1} (LiCl), 0.57 Ω sq^{-1} (NaCl), 0.85 Ω sq^{-1} ($MgCl_2$), 0.67 Ω sq^{-1} ($CaCl_2$), 10.63 Ω sq^{-1} ($MgSO_4$), 508.4 Ω sq^{-1} ($FeSO_4$)	[9]
Custom Ag NP ink (dodecanoate stabilizer)	N_2H_4	PET	Immersing into 80% N_2H_4 solution for 60 min at room temperature and 100 °C	RT: 5 to 10×10^{-6} Ω m 100 °C: 2.5 to 4.5×10^{-6} Ω m	[10]
Custom Ag NP ink (PVP stabilizer), screen printing	NaCl	FR-4	Immersing into NaCl solution in combination with ultrasound for 5 to 70 min	9.91×10^{-6} Ω cm	[11]
Ag NP ink (XjetSolar)	NaCl, $MgCl_2$	PET	Sequential printing of metal and electrolytes (room temperature), variation of number of metal and electrolyte layers	After printing: 5% of bulk Ag After 12 h: 30% of bulk Ag (optimized conditions, *e.g.* multilayer printing)	[12]
Ag NP ink (ANP DGP-45LT-15C)	NaCl	PET, PI	Oven drying (90 °C, 10 min), UV treatment (3 min) for adhesion promotion, then immersion into boiling saturated salt water for 20 min	50% of bulk Ag conductivity	[13]
$CuSO_4$, $AgNO_3$	Ascorbic acid, hydroxylamine	Paper, polyester film,	Sequential printing of multiple layers of metal precursor and reducing ink + hot pressing at 150	Cu: no conductivity (oxidation) Ag: 0.4% of bulk Ag conductivity	[14, 15]

		fabric	°C		
$AgNO_3$	Ethylene glycol vapor Formic acid	PI, PET	Exposure to ethylene glycol vapor at 250 °C, Exposure to formic acid at 150 °C (vapor and sequential printing used)	13.2% of bulk Ag (Ethgly) 8.5% of bulk Ag (formic acid vapor) 3.5% of bulk Ag (printed formic acid)	[16, 17]
Copper citrate $NiSO_4$	$NaBH_4$	paper	Printing cycles of up to 400 times performed, variation of printing cycles, precursor concentration and printing speed	3.3% of bulk Cu 0.2% of bulk Ni at optimized printing conditions	[18]
Ag ammonia	CH_2O	glass	Silver mirror reaction at room temperature and 150 °C, removal of side products with HNO_3	RT: 6% of bulk Ag 150 °C: 14% of bulk Ag	[19]
Ag ammonia	CH_2O / PVP	glass	Silver mirror reaction at room temperature and 150 °C for 60 min, removal of side products with NH_3	RT: 10% of bulk Ag 150 °C: 32% of bulk Ag	[20]
Ag neodecanoate	Hydroquinone, formic acid or ascorbic acid	PET	UV treatment to generate latent image + immersion into reducing solution at room temperature for < 1 min	10% of bulk Ag	[21]
Reactive ink: Diamminesilver (I) cations, acetate as well as formate anions in aqueous solution		Silicon	Self-decomposition of Ag complex at room temperature and 90 °C	2% of bulk Ag conductivity at 90 °C	[22]
Reactive ink: Ag ammonia + diethanolamine (DEA)		PET	Heating above 50 °C to induce self-oxidation of DEA, washing of side products after reaction	75 °C, 20 min: 26% of bulk Ag	[23]
Reactive ink: Ag_2O + silver 2,2 dimethyloctanoate		Glass, PET	Heating to 180 °C triggers recursive reaction of ink, which is exothermic leading to above 300 °C	27 $\mu\Omega$ cm in combination with NaCl sintering	[24]

ESI Table 2 Summary of electrical sintering approaches.

Material	Substrate	Sintering conditions	Performance	Ref
Au-cluster-PEDT composite	Fused silica	40 V (1 MV cm^{-1})	Resistance decrease from 20 kΩ to 300 Ω	25
Ag NP based ink (Silverjet DGP-30LT-15C)	Siena 20 G photopaper	Power density of 100 nW µm^{-3} to initiate sintering with direct current alternating current sintering with high-voltage-probe (100 V at 300 MHz)	3.7×10^{7} S m^{-1} with transition times of 2 µs	26
Ag NP based ink (Silverjet DGP-30LT-15C and Harima NPS-J)	PI, Siena 20 G photopaper	Development of two AC sintering heads with variable power, frequency, sintering speed and number of passes Coaxial head (1.8 GHz, 1 mm s^{-1}, 1 to 10 W) PCB head (2 GHz, 10 mm s^{-1})	1 Ω sq^{-1} for coaxial head operated at 10 W (Silverjet on PI) 120 mΩ sq^{-1} for PCB head operated at 10 W (Harima on PI) 60 Ω sq^{-1} for PCB head operated at 10 W (Silverjet on paper)	27
DuPont CB028 silver conductor Ercon E1660 (silver flake ink	PI	Variation of current density (0.30 to 0.5 mA µm^{-2}) and time (30 to 60 s)	40 to 358 nΩ m with optimized settings for each ink	28
Ag NP based ink (Harima NPS-J)	photopaper	Variation of initial resistance (100 Ω to 1 MΩ), input voltage (0 to 65 V) and sequences (multi-step)), pre-sintering at 100 °C between 5 and 10 min	Not specified	29

ESI Table 3 Summary of plasma sintering approaches.

Material	Substrate	Sintering conditions	Performance	Ref
$AuCl_3$ ink / spin coating	Nylon 66	Custom plasma chamber, H_2 discharge (13.56 MHz radio frequency power source), low-pressure (0.15 mbar), 30 W	3×10^{-5} Ω cm	30
Ag NP based ink (Harima)	PC, glass, PET	Commercial plasma asher (Emitech Ltd.), Argon	10% of bulk Ag on foil	31

		plasma, radio frequency power source (13.56 MHz), 40 to 80 W, low-pressure (1 mbar working pressure), up to 120 min processing time	30% of bulk Ag on glass	
$AgNO_3$, Pd acetate	glass	Custom plasma chamber, H_2 plasma, 30 min processing time, low-pressure (13.56 MHz radio frequency power source), low-pressure (0.15 mbar), 10 W	21% of bulk Ag 4% of bulk Pd	32
Ag NP based inks (Cabot CCI-300, Harima NPS-J, custom ink (10 nm, 30 wt%)	PEN, PI	Atmospheric-pressure plasma (kinpen, neoplas tools GmbH), argon plasma, high frequency power supply (1.1 MHz, 2 to 6 kV), variation of number of passes (1 to 150, up to 2 min processing time)	Cabot: 16.1 μΩ cm Harima: 25.4 μΩ cm Custom: 13 μΩ cm for optimized sintering settings	33
$AgNO_3$	glass	Low-pressure plasma (13.3 Pa), PE200RIE PlasmaEtch, Argon plasma, 13.56 MHz radio frequency power source, max. 900 W	50 to 95% of bulk Ag for top crust layer, significantly overall conductivity (not specified)	34
Ag NP based inks (Cabot-CCI-300, Harima NPS-JL)	PET, P(VDF-TrFE)	Low-pressure (0.2 to 0.4 mbar) argon plasma (Diener Electric), 300 W, 40 kHz generator, 30 min sintering pre-drying of the ink at 100 °C for 60 min	20 to 30% of bulk Ag conductivity	35
Ag NP based ink (AGFA)	PET, glass	Low-pressure (0.2 to 0.4 mbar) argon plasma (Diener Electric), 150 - 300 W, 40 kHz generator, for 1 to 60 min	11.4% of bulk Ag (1 min, 300 W) 40% of bulk Ag (60 min, 300 W)	36
Ag NP based inks (Cabot CCI-300, Harima NPS-J)	PP	Low-pressure (0.2 to 0.4 mbar) argon plasma (Diener Electric), 300 W, 40 kHz generator, for 5 to 30 min	0.083 S over 1.2 mm (Cabot) 0.29 S over 1.2 mm (Harima)	37
Custom Cu NP based screen printing paste (PVP stabilizer)	PI	Two stage plasma sintering (1. O_2 plasma, 2. H_2 plasma, 20 min each), atmospheric pressure plasma equipment (RF glow discharge plasma) 100 to 300 W, 5 mm min^{-1}, 150 °C substrate temperature	8% of bulk Cu (250 W, 40 min)	38
Ag NP based ink (Cabot CCI-300)	PEN	Low-pressure (0.2 to 0.4 mbar) argon plasma (Diener Electric), 300 W, 40 kHz generator, for 1 to 60 min Atmospheric-pressure plasma (kinpen, neoplas tools	Kinpen: 10.4 μΩ cm (110 °C substrate T, 20 passes), 15.5 μΩ cm (110 °C, 1 pass)	39

		GmbH), argon plasma, high frequency power supply (1.1 MHz, 2 to 6 kV) Atmospheric-pressure plasma (plasma blaster, Tigres), argon plasma, plasma temperature 200 °C, variable substrate heating (< 110 °C), 1 to 5 passes	Tigres: 27.2 μΩ cm (90 °C, 1 pass), 12 μΩ cm (110 °C, 1 pass)	
Custom Ag NP based inks (23 nm and 77 nm average particle size)	glass	RF (13.56 MHz) plasma chamber (Nextral 500), Argon plasma, 100 to 900 W, 5 to 60 min	20% of bulk Ag for 23 nm ink (900 W, 60 min) 8% of bulk Ag for 77 nm ink (900 W, 60 min)	40

ESI Table 4 Summary of IR sintering approaches.

Material	Substrate	Sintering conditions	Performance	Ref
Ag NP based inkjet ink (20 wt%), SunTronic U5603	Glass, paper	Long wavelength IR (8 to 15 μm), 5 passes for each sample, 180 °C surface temperature (3 to 5 min IR treatment)	2 Ω sq^{-1} in less than 3 min	41
Ag NP ink (InkTech TEC-PR-030), slot-die-coating	PET	NIR sintering between 1.4 and 2.4 s (lamps: Adphos NIR/IR Coil lab LV2) IR sintering between 17 and 84 s (lamps: SC Driers UV/IR), time adjustable by speed of conveyor belt, power not specified	IR: 32 mΩ sq^{-1} (84 s treatment time) NIR: 26 mΩ sq^{-1} (2.1 s treatment time)	42
Ag NP based inkjet ink (20 wt%), SunTronic U5603, Custom Au NP based ink	Paper (kaolin coated), glass, PET	Setup A: 30 cm long 2kW strip light bulbs (IRT System Hedson Technologies AB), 2 to 4 W cm^{-2}, distance to sample 15 cm Setup B: strip light bulbs (Ceramics HQE), max power 500 W, distance variation (3 to 20 cm), time 5 to 25 s (180 °C substrate temperature)	PET deformation during sintering 10% of bulk Au on paper 20% of bulk Ag on paper in 20 s (slight degradation observed)	43-51

ESI Table 5 Summary of UV assisted sintering approaches.

Material	Substrate	Sintering conditions	Performance	Ref
Ag neodecanoate + hydroquinone or formic acid or ascorbic acid	PET	UV treatment to generate latent image + immersion into reducing solution at room temperature for < 1 min	10% of bulk Ag	21
($Ag_2O(CH_2OCH_2)_3H$)	Glass, PET	UV light, 70 mW cm^{-2} in addition to thermal treatment (100 to 130 °C) for 30 min	PET: 18% of bulk Ag (130 °C, 30 min)	52, 53
$[Ag(DiocoNic)_2]NO_3$	Glass	UV treatment (power not specified) for 40 min and subsequent thermal sintering at 250 °C for 60 min	90% of bulk Ag	54

ESI Table 6 Summary of laser sintering approaches.

Material	Substrate	Sintering conditions	Performance	Ref
Au NP based ink	Glass	Argon ion laser (488 nm), spot size 10 to100 µm, 1 mm s^{-1} writing speed, 50-300 mW	1.4×10^{-7} Ωm	55
Au NP based ink	Glass	Continuous wave (argon ion) laser (488 to 515 nm), spot size 5 µm, 8 to 18 mW, 20 to 120 µm s^{-1} writing speed	2 to 5×10^{-6} Ωm at 8.8 mW and 25 µm s^{-1}	56
Au NP based ink	Glass	Argon ion laser (514 nm), spot size 8 µm, 9 to 14 kW cm^{-2}	Investigation on morphology of sintered Au lines (no conductivity mentioned)	57
Au NP based ink	Glass	Argon ion laser, (188-515 nm), spot size 8 to 17 µm, 50 to 500 mW, 1 to 2 mm s^{-1} writing speed	17% of bulk Au (conditions not specified), high laser power leads to defects in the pattern	58, 59
Au NP based ink (hexanethiol stabilizer)	PI	Nd:YAG laser (3 to 5 ns pulse width, 532 nm, 15 Hz) for ablation Continuous wave (argon ion) laser (514 nm), 0.1 mm s^{-1} writing speed, 15 to110 mW, spot size 1 to 2 µm	Damage of the substrate > 100 mW 50% of bulk Au (25 mW = 3.43 kW cm^{-2})	60-63
Cu NP based ink	Glass	Argon ion laser (488 nm), writing speed varied between 100	7.2×10^{2} Ωcm (100 µm s^{-1})	64

(Nanometalink, ULVAC)		to 2000 μm s^{-1}, spot size 0.78 mm	3.28×10^{-5} Ωcm (2000 μm s^{-1})	
Custom Ag NP based ink Custom AG-Cu NP based ink	Poly(ether sulfone)	Ar ion laser (488 nm), 0 to 400 mW, 30 to 90 min treatment time, partial removal of PVP stabilizer with acetone / methanol prior to printing	Ag: 25 μΩ cm at 400 mW for 30 min Ag-Cu: 30 μΩ cm at 400 mW for 90 min	[65]
Au NP based ink	Glass	Continuous wave (argon ion) laser (514 nm), beam size 3 mm, 1 to 1.9 W, 1 mm s^{-1} writing speed	16.8 μΩ cm at 26.89 W cm^{-2}	[66]
Custom Ag MOD ink	PI	Yb doped fiber laser (1071 nm), 50 to 600 mW, 10 mm s^{-1} writing speed, spot size 60 μm, local temperature > 170 °C	25% of bulk Ag conductivity (500 mW) Substrate damage at > 500 mW	[67]
Ag NP based ink	Si (100) wafers	Annealing at 100 °C for 60 min prior to laser sintering, Nd:YAG continuous wave laser (1064 nm) max power (density) 500 W (1.5×10^{6} W cm^{-1}), variation of defocussing (0 to 40 mm),	3 μΩ cm at 38 mm defocussing, two passes, > 5.67×10^{5} W cm^{-2}	[68]
Ag NP based ink	PI	Laser 1: pulsed laser (515 nm), 30 to 600 mW, 10 to 300 mm s^{-1} writing speed, scanning angle 0°, 45°, step size 5 to 20 μm Laser 2: continuous wave diode laser (980 nm), 9 to180 W, 1 to 150 mm s^{-1} writing speed, 135 to 230 °C	5 μΩ cm with: Laser 1: 2 step procedure (solvent evaporation, sintering) Laser 2: 180 °C Result comparable to thermal sintering at 220 °C	[69]
Custom Ag NP based ink (alkylammonium stabilizer)	Silicon wafer	Ti:sapphire femtosecond laser (780 nm, 100 fs), repetition rate 80 MHz, 2.5 to 10×10^{10} W cm^{-2}, 100 to 600 μm s^{-1} writing speed, spot size (line width) 380 nm	1.8×10^{-5} Ω cm (≈ 9% of bulk Ag) at 400 mW (not further specified)	[70, 71]
Ag NP based ink (Harima NPS-J)	PI, Cu	Laser 1: continuous wave Nd:YAG laser (1064 nm), 4 mm s^{-1} writing speed, max power 130 W, Laser 2: diode laser (980 nm), Laser 3: green laser (532 nm), 5 W	Laser 1: not specified Laser 2: 5 μΩ cm on PI at > 3 W Laser 3: not specified Laser 4: 8 μΩ cm on PI at 0.4 W	[72]

		Laser 4: Ar ion laser (488 nm), 1.4 W	All show good adhesion	
Ag NP based ink (Advanced Nano Products)	Al_2O_3, PI	Nd:YAG pulsed laser (1064 nm), 63 µm spot size, variation of power (0.1 to 8W), pulse energy (0.5 to 37.5 µJ), pulse repetition rate (0.1 to 90 kHz), pulse duration (1 to 7 µs) and writing speed (5 to 10 mm s^{-1})	PI: 20% of bulk Ag conductivity (0.5 µJ, 1 kHz, 5 µs, 10 mm s^{-1}); Al_2O_3: 10-14% of bulk Ag conductivity (90 kHz, 5 µs)	[73]
Ag NP based ink (InkA-GP, Politronica Inkjet printing)	PI	Continuous wave Nd:YVO4 laser (1064 nm), 1.12 to 2.83 kW cm^{-2}, 0.5 to 1.5 mm s^{-1} writing speed, spot site 52 µm	32.6% of bulk Ag conductivity (1.12 kW cm^{-2}, thick films (8 layers), 0.5 mm s^{-1})	[74]
Ag MOD ink (InkTech, Tech-Co-010)	Glass, polymer (not specified)	Pre-baking to transform transparent MOD into NPs, two lasers employed (532 nm, 1070 nm), 10 µm spot size, 10 mm s^{-1} writing speed, 35 to 40 mW	532 nm: Explosive vaporization of residual organics 1070: Smooth patterns with 5.7 µΩ cm	[75]
Custom Ag NP based ink	Silicon wafer, glass	Millisecond Nd:YAG pulsed laser (1064 nm), 100 to 200 W, pulse width 1 ms, repetition rate 200 Hz, beam size 0.6 mm,	No electrical measurements included, Temperature determined inside of the ink (440 °C)	[76]
Custom Ag NP based ink / spin coating, slot die coating, gravure	Glass, PI, PET, PEN	Continuous wave Ar ion laser (514.5 nm) and cw Nd:YAG laser (532 nm), up to 1 m s^{-1} writing speed (2D galvanometric mirror system), 0 to 400 mW	Up to 76% bulk Ag conductivity below 100 mW Larger area processing (5x5 cm) in 3 min	[77-79]
Ag NP based ink	Display glass (Eagle-XG (Samsung-Corning)	Continuous wave laser (not further specified) at 532 nm, variation of intensity (121 to 585 W cm^{-2}) for 60 s	39.2% of bulk Ag at 467 W cm^{-2} for 60 s Ink temperatures between 191 °C and 325 °C at different intensities (exact conductivity not provided for each setting).	[80]
Cu NP based ink (CI-002, Intrinsiq Materials Ltd.)	Glass	Continuous wave Nd:YAG laser (wavelength unknown), power variation (200 to 600 mW), 0.3 to 20 mm s^{-1} writing speed for sintering	200 mW: 1.2%; 300 mW: 11.5%, 400 mw: 15.2%, 500 mW: 19.6%, 600 mW: 22.2% of bulk Cu	[81]

		Pulsed wave Nd:YAG laser for ablation	conductivity Higher writing speeds yield in higher conductivity	
Custom Ag NP based ink	Glass	Continuous wave Nd:YAG (532 nm) laser, scanning by digital micromirror device (shaping of laser beam) for 2D manufacturing, further settings not provided	10.8 µΩ cm (settings not specified)	[82]

ESI Table 7 Summary of IPL sintering approaches.

Material	Substrate	Flash conditions	Performance	Ref
Ag NP based inkjet inks (20 and 40 wt%) Cabot CCI-300, Xerox Nano-AG-1201	Various types of paper	PulseForge, process details not specified	200 to 600 nm 0.7×10^{7} S m^{-1} (Xerox), 0.9×10^{-6} Ω cm (Cabot)	[83]
Ag NP based inkjet ink, Harima NPS-J	PC and PI	Xe lamp, Holst tool, 1 kW, 35 to 50 Hz, 10 ms pulses, 10 to 40 s	3.3 to 3.8×10^{-6} Ω cm (min), 7.1 to 13.6×10^{-6} Ohm cm (max), good adhesion	[84]
Ag NP based inkjet ink (20 wt%), SunTronic U5603	PEN	Xe lamp, Holst tool, 500 W, 10 s, 10 ms pulses, varying number of flashes	5.7×10^{-6} Ωcm (pre-treatment)	[85]
Ag based inkjet inks, AgSt2 Novacentrix, UTDot	Not specified	Xe lamp, Novacentrix PCS-1100, 1200 V, pulse length 900 µs	2.8×10^{-6} Ωcm (UTDot), 7.9×10^{-6} Ω cm (AgSt2)	[86]
Ag NP based inkjet ink (20 wt%), SunTronic U5603	Glass and PEN	Xe lamp, Holst tool, 5 s, max. power 1000 W, max., 17 Hz	Reduced line width (260 vs. 290 micron), 9×bulk Ag	[87]
Ag NP based gravure-offset ink (ANP GDP-OS(12000)), 67 wt%	PET	Xe lamp, DIY setup, up to 99 flashes, energy density 0.75 to 3.5 J cm^{-2}, pulse duration 1.5 to 6 ms, off-time 20 to 0 ms, pulse number variation, total time < 1 s	0.95 Ω sq^{-1} (single pulse, 1.5 ms, 3 J cm^{-2}), In-situ R measurement	[88]
Ag NP based inkjet ink (20 wt%), SunTronic U5603	PEN	Xe lamp, Holst tool, Pulse length 3-8 ms, 2 to 17 Hz, int. 0 to 1000 W,	Reduced line width, 16% bulk Ag under optimized conditions. In-situ R and T measurement	[89]

Ag NP based inkjet ink (57 wt%) Harima	PI	Xe lamp, DIY setup, sequenced flashing with single pulse sintering step. Total energy 10-20 J cm^{-2}. Preheating 15 flashes 5 ms on, 30 ms off	36.32 nΩ m (15 pulses, 10 J cm^{-2} + 1 pulse 20 J cm^{-2})	90
Ag NP based inkjet ink (57 wt%) Harima	PI	Xe lamp, DIY setup, energy 5 to 30 J cm^{-2}, pulse length 5 ms, 100 Hz	No resistivity determined due to foil deformation. Achieved resistances under optimized cond. (20 J cm^{-2}) ca. 50% higher than 210 °C for 1 h	91
Custom Ag NP based inkjet ink (14 wt%)	PI, PET, paper	Xe lamp, pulse length 1 ms, number of pulses varied from 1 to 5	6.2×10^{-6} Ω cm (PET), 7.2×10^{-6} Ω cm (PI), 10.5×10^{-6} Ω cm (paper)	92
Ag NP based inkjet ink (30 wt%) ANP Silverjet DGP-40LT-15C	p-type Si(100)	Moving halogen lamp (max. 2400 W), 10-300 W, lamp speed 0.4 to 4 cm min^{-1}. No flashing	Includes some rudimentary T measurements. 70.2×10^{-6} Ωcm (25 W) to 2.64×10^{-6} Ω cm (300 W)	93
Custom Ag NP based inkjet ink (50 wt%)	PI and glass fiber reinforced polymer composite (GFRPC)	Xe flash lamp, var. energy density (20-50 J cm^{-2}), pulse length 4 or 6 ms, up to three pulses, 5 ms break	Single pulse, 50 J cm^{-2}: 186 nΩ m Two pulses, 50 J cm^{-2}: 89 nΩ m Three pulses, 50 J cm^{-2}: 47 nΩ m, good adhesion	94
Custom Ag NP based inkjet ink (20 wt%)	PI, PET	Studio Flash 1200 Ws GN1201, 1200 J/pulse, 250 µs pulse length, variation of number of pulses and distance to lamp	No conductivity values reported	95
Custom Ag NP based inkjet ink (40 wt%)	PET, PVC	Xenon Sinteron 500, 800 J/pulse, 500 µs pulse duration, varying pulse number (1 to 3)	No conductivity values reported	96
Suntronic U5603 (20 wt% Ag NP) Inktec IJ-040 (20 wt% Ag complex) Cu complex solution (18	PEN (Ag), glass (Cu)	Philips XOP-50, 10 ms pulse duration, 750 W, 15 Hz, total time 16 s (IJ-040), 5 s (U5603) Cu: 30-60 s (in air) R2R 1.5 m min^{-1} (U5603)	28% bulk Ag (both Ag IJ inks) 10^{-6} times bulk Cu resistivity (oxidation) R2R: 20% bulk Ag (U5603)	97

wt% Cu)				
Ag NP flexo inks (PFI-722, PChem, 60 wt%, and 25 wt% in organic solvents), R2R flexo	Barrier foil for OPV	Pre-drying by hot air (140 °C) and IR Single flash and R2R flash sintering on Xenon Sinteron 2000, max. 830 J/pulse, 0.5 ms. R2R: web speed 1.0 to 2.5 m min^{-1}, 3.0 kV, 1.8 Hz, 0.5 ms. 1 m min^{-1}, 1.8 Hz, 2.0 to 3.0 kV, 0.5 ms	PFI-722: 1.15 Ω sq^{-1} at single flash 1.75 J cm^{-2} (from 1.55 Ω m after pre-drying). Ag NP ink: 6.8 Ω sq^{-1} at single pulse 0.95 J cm^{-2}, improved adhesion. R2R sintering only for Ag np: 3.0 kV, 1.0 m s^{-1} gave 7 Ω sq^{-1}	98
Ag NP inkjet ink (Suntronic U7089), 20 wt%, R2R inkjet	PET	Web speed 2 m min^{-1}, two times 1 min 140 °C drying Xenon Sinteron 2000, 0.5 ms, 1.8 Hz, 830 J/pulse. Web speed 0.5, 1.0, 2.0 m min^{-1}	9-12 Ω sq^{-1} for 0.5 m min^{-1}	99
Ag NP based inkjet inks Suntronic U5603 (20 wt%), UTDAg25 (25 wt%), ULvac L-Ag1TeH (55 wt%)	PEN	SAT: Philips XOP-50 10 Hz, 5 ms, 600 W S2S: 2 XOP-50 + Sinteron 2000, 0-20 m min^{-1} R2R: NIR + 4 XOP-50 + Sinteron 500, web speed up to 10 m min^{-1}	U5603: 12% bulk Ag within 5 s UTDAg25: No cond. L-Ag1TeH: Very strong foil deformation S2S: 12% bulk Ag (U5603) R2R: 12% bulk Ag (U5603)	100
Suntronic U5603 (20 wt% Ag NP)	PC	Novacentrix Pulse Forge 3100, optimized flashing conditions (not specified), R2R speed 10 m min^{-1}	9.6 Ω cm^{-1} (no conductivity specified), < 3 s	101
Suntronic U5603 (20 wt% Ag NP)	PI PI, PC, PEN, PET, PP	Xenon Sinteron 2000, flash energy 190 to 590 J, 1 to 6 Hz, total time 2 to 30 s Different illumination spectra (350 J/pulse, 0.58 ms pulse width, 2 Hz) Energy and frequency variation	4 Ω cm at optimized conditions (350 J/pulse, 3-4 Hz, 2 s), no cond. specified Blue emission gave best results (fast sintering and no line cracking) Line structure, no conductance	102
Custom Ag and Cu NP dispersions, wire bar coated	PET	Pulse lengths variation (30 to 100 to 300 µs), energy density 0.31 to 1.65 J cm^{-2}	Ag: 20 mΩ sq^{-1} (25% bulk Ag) under optimized conditions (100 µs, 1.13 J cm^{-2}) Cu: 72 mΩ sq^{-1} (9% bulk Ag) under optimized conditions (30 µs, 0.77 J cm^{-2})	103

Custom Ag NW dispersion (wt% not rep.), wire bar coating or drop casting	PET	Novacentrix Pulse Forge 3300, 50 µs pulse length, energy density 0.21 to 2.33 J cm^{-2}, pulse time variation 50 to 250 to 500 µs	Good adhesion at > 1.14 J cm^{-2}. 1 MΩ sq^{-1} (unsintered) to 5.3 Ω sq^{-1} for 2.33 J cm^{-2}. Unchanged transparency up to 1.14 J cm^{-2} (> 82 %), 55 % for 2.33 J cm^{-2} (PET degradation), good bending stability for > 0.74 J cm^{-2}. Lower Rsq for longer pulses. T calculation	[104]
Custom Ag NW dispersion (wt% not rep.), wire bar coating	Glass and PET, also PI, PC, PVC	Novacentrix Pulse Forge 3300, 50 µs pulse length, energy density 0.074 to 1.14 J cm^{-2}	Lower Rsq for higher intensity. Stronger intensity dependence for PET (20 Ω sq^{-1} vs. 45 Ω sq^{-1} at 1.14 J cm^{-2}), T > 82 %. T calculation to support influence of thermal properties of substrate. Best adhesion on substrates with low Tg. Long exposure times result in substrate degradation	[105]
Custom Ag NW dispersion (wt% not rep.), spray coated	glass and PE (SiN membrane for EM char.)	W halogen lamp, 30 W cm^{-2}, 10 to 120 s, no flashing. Time dependence of film resistance	1000 fold decrease in film resistance after 60 s, at almost unchanged transparency. 10 Ω sq^{-1} at 80 % T	[106]
Dispersion of commercial Cu NP (28 to 49 wt%), spin coated	PI	Dried samples (120 °C, 15 min, N_2) Pulse energy (10 to 20 J cm^{-2}), number of pulses (1 to 3), Pulse time (5 to 20 ms). In air	Optimal performance 0.072 Ω sq^{-1} at 12.5 J cm^{-2}, single pulse, 10 ms. Very limited (re)oxidation, oxide reduction by PVP. Film thickness not specified Real time sheet resistance monitoring	[107]
Dispersion of commercial Cu NP (wt% not specified)	PI	Self-built setup with Xe lamp, min. pulse duration 2 ms, max. energy density 100 J cm^{-2}, var. of intensity, frequency, pulse length, number of pulses. In air	Oxide reduction by PVP, substrate damage at too high energy exposures, 1.73×10^{-6} Ω m	[108]

Dispersion of commercial Cu np (16 wt%), drop cast and inkjet print	PI	Self-built setup with Xe lamp, pulse duration 2 ms, energy density 50 J cm^{-2}. In air	Oxide reduction by PVP, 5×10^{-6} Ω cm	[109]
Dispersion of Cu NP (no Cu load rep.), deposition *via* pipetting and stamp printing	Glass fibre BT epoxy composite, PI, PE, PP	Self-built setup with Xe lamp, pulse duration 2 ms, energy density 20 to 50 J cm^{-2}. In air	No signs of oxidation, 5×10^{-6} Ω cm at 50 J cm^{-2}, good adhesion to polymers	[110]
Proprietary Cu NP formulation, Cu load not specified, film coating	PI	Mask illumination, total time < 1 ms, conditions not specified	1.24 to 1.95×10^{7} S m^{-1}	[111]
Custom dispersion of Cu NP, solid fraction ca. 50 vol%, spray coating on heated (160 °C) substrates	Glass, PET	Sinteron 2000 (Xenon), pulse duration 0.58-2.00 ms, max. freq. 10 Hz, energy density 10.2 to 34.5 J cm^{-2}, 10 pulses per energy, cumulative (glass under N_2). Single pulse, 2 ms, 22.4 J cm^{-2} (PET in air)	Glass: 0.118 Ω sq^{-1} (1723 J cm^{-2}), 9.4×10^{-5} Ω cm PET: 1.35 Ω sq^{-1} at 4 µm thickness Partial Cu_2O reduction to Cu by decomposition products of organic ink components	[112]
Cu formate (15 wt%), Cu acetate (16 wt%), Cu oleate (7.5 wt%) in diethanolamine 1 : 2 molar mixture, mask printing	glass	Novacentrix PulseForge 3300, in air, 1.4 ms pulse, 2.69 J cm^{-2}, 6 pulses (formate), 10 pulses (acetate), 16 pulses (oleate), frequency not specified	Surface oxidation, 5.6×10^{-5}Ω cm (formate), 2.1×10^{-2} Ω cm (acetate), no cond. (oleate)	[113]
Custom mixture of $Cu(OH)_2$, formic acid and citric acid in aq. NH_3. Formulation into inkjet ink by addition of solvents and PVP. Roller ball and inkjet deposition	PET, PI	In air. IPL system, details not disclosed, pulse width 1.5 ms, frequency 32 and 74 Hz, 17 to 46 pulses, pulse energy density 0.69 to 1.79 J cm^{-2}	3.21×10^{-6} Ω cm at total energy density of 50.5 J cm^{-2}. Oxide removal from 40.6 J cm^{-2} on	[114]

CuO particle based inkjet ink (16wt% CuO, 12.8 wt% Cu)	Coated PET	IR pre-drying (6 kW), PulseForge 3200 X2, Novacentrix (uniform), or pulse shaping. Power variation, number of pulses varied. Substrate movement 12 to 18 cm s^{-1}	Optimized conditions gave 9.5 Ω cm^{-1} for IR pre-drying and uniform pulsing. 11.5 Ω cm for optimized pulse shaping. No conductivity values specified.	115
CuO NP based inkjet ink (16wt% CuO, 12.8 wt% Cu)	Coated PET	PulseForge 3200, Novacentrix (Xe flash lamps). Vary number of pulses (1 to 3), pulse length 6, 3, 2, ms, freq. 10 Hz. Energy variation	Optimized conditions: Single pulse: 0.39 Ω sq^{-1} Double pulse: 0.14 Ω sq^{-1} Triple pulse: 0.12 Ω sq^{-1} Partial delamination for too high energies. Film thickness not reported	116
CuO particle based inkjet ink (16wt% CuO, 12.8 wt% Cu)	Coated PET	PulseForge 3100, Novacentrix, 10 ms pulse duration, 7.6 J cm^{-2}	30 × bulk Cu resistivity	117
CuO particle based inkjet ink (16wt% CuO, 12.8 wt% Cu)	Coated PET	PulseForge 3200, Novacentrix, in air No pre-drying < 1 s total time Vary number of pulses (1, 2, 3), pulse length 6, 3, 2, ms, freq. 10 Hz. Energy variation	Optimized conditions: Single pulse: 0.39 Ω sq^{-1} Double pulse: 0.14 Ω sq^{-1} Triple pulse: 0.12 Ω sq^{-1} Partial delamination for too high energies. Lowest resistivity 55.4×10^{-9} Ω m at 3 x 2 ms pulses with 8 J cm^{-2} Partial delamination for too high energies.	118
Self-synthesised Au np dispersion (1 wt%), deposition with pen	Coated paper	Thermal drying (80 °C), camera flash sintering, pulse length 0.1 to 10 ms, energy density 1.55 to 2.7 J cm^{-2}	50 Ω per 4 mm	119
Two types of commercial Ni NP (uniform 50 nm, polydisperse 5-500 nm), dispersed in organic	PI, paper	Pre-drying 20 min at 150 °C. Xe lamp, DIY setup, energy density 7.5 to 17.5 J cm^{-2} Two step sintering: 1.15 pulses, 5 ms, 28.5 Hz. 2. Single pulse sintering.	0.35 Ω sq^{-1} for optimized conditions (15 × 12.5 J cm^{-2} + 1×17.5 J cm^{-2}) with polydisperse ink	120

solvents. Spin coating an screen printing				

ESI Table 8 Summary of microwave sintering approaches.

Material	Substrate	Flash conditions	Performance	Ref
Ag NP based ink (Harima)	PI	Sintering in capped vial at 2.45 GHz (Emrys Liberator monomodal microwave, Biotage), power 300 W	5% of bulk Ag conductivity at 300 W for 240 s	[121]
Ag NP based ink (Cabot CCI-300)	PEN	Sintering in capped vial at 2.45 GHz (Emrys Liberator monomodal microwave, Biotage), max power 1 W for 1 to 60 s, conductive Ag antennas as susceptor, thermal pre-sintering at 110 °C for 1 to 5 min	Optimized settings (44 mm^2 antennas, 1 s, 1 W): 34% of bulk Ag conductivity	[122]
Suntronic U5603 (20 wt% Ag NP)	n-type (100) silicon	Hybrid variable frequency (6.425± 0.75 GHz) microwave (HVFM) sintering with MicroCure 2100 oven (Lambda Technologies), silicon substrate as susceptor, 130 to 300 °C, variation of heating rates,	2.1 μΩ cm after 15 min at 300 °C (10 °C s^{-1}) Final conductivity dependent on substrate temperatures Resistivity below 10 μΩ cm for all applied temperatures	[123]
Suntronic U5603 (20 wt% Ag NP)	PEN	Thermal pre-sintering at 110 to 140 °C for 20 to 300 s, IPL pre-sintering (Holst tool) with max power of 1 kW, pulse length 10 ms, 32 flashes/pulse, 12 to 21 flashes (10 s) Microwave sintering 1: Emrys Liberator monomodal microwave (2.45 GHz), Biotage, max power 1 W for 1 to 60 s, conductive Ag antennas as susceptor Microwave sintering 2: Milestone Ethos CFR	Biotage: 1.5 to 35% of bulk Ag (thermal pre-sintering) 2.5 to 44% of bulk Ag (IPL pre-sintering) Milestone: 5% of bulk Ag (IPL pre-sintering)	[85]

		(2.45 GHz), 10 W, 3 s		
Custom Ag NP ink	Glass, PEN	Plasma pre-sintering (Diener Electric low pressure chamber), 150 to 300W for 1-12 min Microwave sintering 1: Emrys Liberator monomodal microwave (2.45 GHz), Biotage, max power 1 W for 1 s, conductive Ag antennas as susceptor	60% of bulk Ag	124

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Table of Contents / Graphical Abstract

This review discusses the advances in alternative sintering approaches for conductive, metal containing inkjet inks. Each sintering approach is examined regarding its mechanism, its compatibility with materials in the field of flexible electronics and its compatibility with high-throughput manufacturing processes.