

Electrical Properties of Conductive Traces Made From Silver-based Molecular Inks

Example	Molecular Weight Ethyl Cellulose (g/mol)	Concentration Ethyl Cellulose (wt%)	Solvent	Sheet Resistance (mΩ/sqr)	Trace Thickness (μm)	Volume Resistivity (μΩ·cm)	Sheet Resistivity (mΩ/sqr/mil)
C1	None	0	Xylene	47.6	0.7	3.3	1.33
E1	~65000	5	Xylene	56.1	1.32	7.4	2.92
E2	~65000	2.5	Xylene	47.7	1.24	5.9	2.33
E3	~65000	1.25	Xylene	35.4	1.24	4.4	1.73
E4	~65000	0.25	Xylene	30.7	1.08	3.3	1.31
E5	~96000	2.5	Xylene	61.1	-	-	-
E6	~96000	1.25	Xylene	35.5	-	-	-
E7	~96000	0.25	Xylene	38.9	-	-	-
E8	~96000	2.5	Toluene	117	0.67	7.5	2.9
E9	~65000	5	Xylene:Terpineol (3:1)	63.3	2.7	17.4	-
E10	~65000	5	Xylene:Terpineol (1:1)	80.4	1.62	13.1	-
E11	~65000/~96000 (7:1)	5	Xylene:Terpineol (7:1)	202	0.62	11.6	4.5

Fig. 1A

Mechanical Properties of Conductive Traces Made From Silver-based Molecular Inks

Example	Molecular Weight Ethyl Cellulose (g/mol)	Concentration Ethyl Cellulose (wt%)	Solvent	Tensile Flex (Resistance Change, %)	Compressive Flex (Resistance Change, %)	Tensile crease (Resistance Change, %)	Compressive Crease (Resistance Change, %)
C1	None	0	Xylene	less than 10%	less than 10%	less than 10%	FAIL
E1	~65000	5	Xylene	less than 10%	less than 10%	less than 10%	FAIL
E2	~65000	2.5	Xylene	less than 10%	less than 10%	greater than 10%	greater than 20%
E3	~65000	1.25	Xylene	less than 10%	less than 10%	less than 10%	less than 10%
E4	~65000	0.25	Xylene	less than 10%	less than 10%	less than 10%	greater than 40%
E5	~96000	2.5	Xylene	less than 10%	less than 10%	less than 10%	FAIL
E6	~96000	1.25	Xylene	less than 10%	less than 10%	FAIL	FAIL
E7	~96000	0.25	Xylene	less than 10%	greater than 10%	less than 10%	FAIL
E8	~96000	2.5	Toluene	less than 10%	greater than 10%	greater than 10%	FAIL
E9	~65000	5	Xylene:Terpineol (3:1)	less than 10%	less than 10%	less than 10%	greater than 100%
E10	~65000	5	Xylene:Terpineol (1:1)	less than 10%	less than 10%	greater than 10%	FAIL
E11	~65000/~96000 (7:1)	5	Xylene:Terpineol (7:1)	less than 10%	less than 10%	greater than 10%	greater than 50%
				less than 10%	less than 10%	greater than 40%	greater than 100%
				less than 10%	less than 10%	less than 10%	FAIL
				less than 10%	less than 10%	less than 10%	FAIL
				less than 10%	less than 10%	less than 10%	FAIL
				less than 10%	less than 10%	less than 10%	greater than 50%
				less than 10%	less than 10%	less than 10%	greater than 100%
				less than 10%	less than 10%	less than 10%	greater than 50%
				less than 10%	less than 10%	less than 10%	greater than 100%
				less than 10%	less than 10%	less than 10%	greater than 50%
				less than 10%	less than 10%	less than 10%	greater than 100%
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				less than 10%	less than 10%	less than 10%	greater than 100%
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				less than 10%	less than 10%	less than 10%	greater than 50%
				less than 10%	less than 10%	less than 10%	greater than 100%
				less than 10%	less than 10%	less than 10%	greater than 50%
				less than 10%	less than 10%	less than 10%	greater than 100%
				less than 10%	less than 10%	less than 10%	greater than 50%

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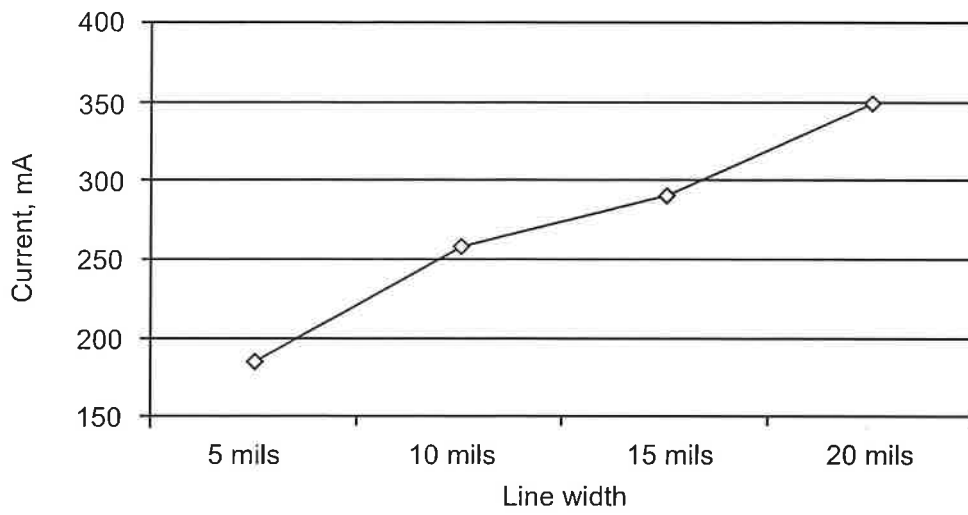


Fig. 1C

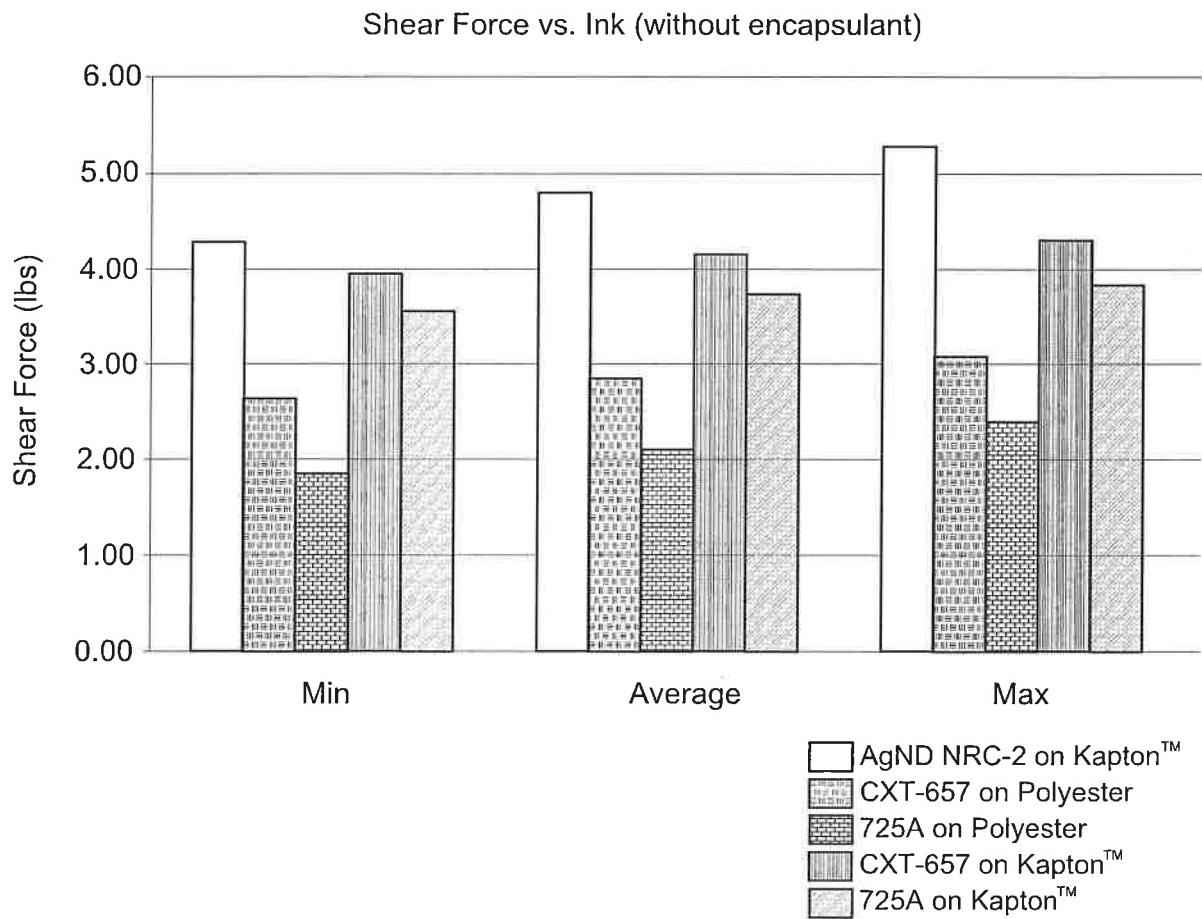


Fig. 1D

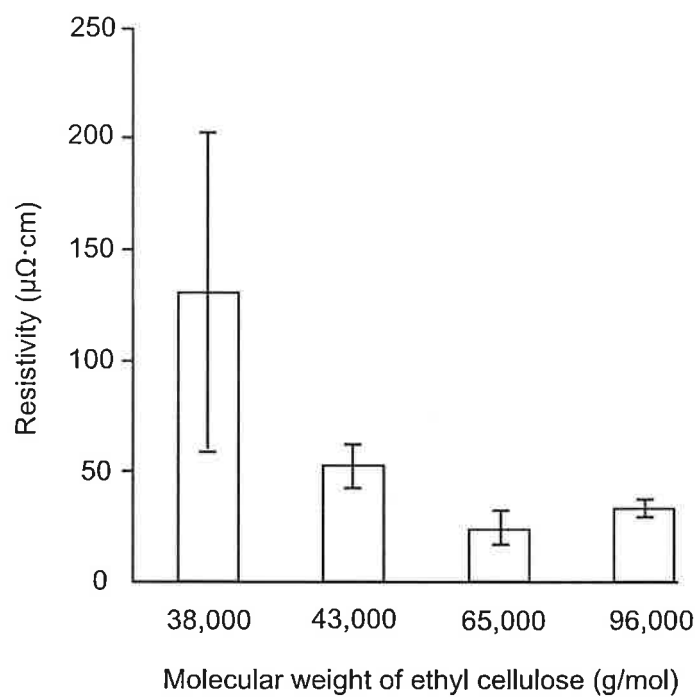


Fig. 2A

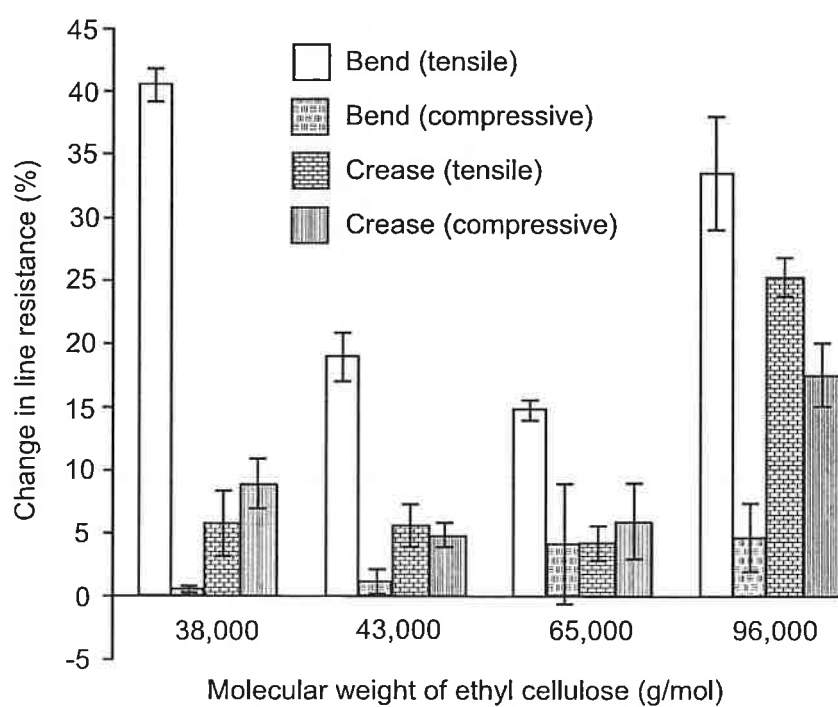


Fig. 2B

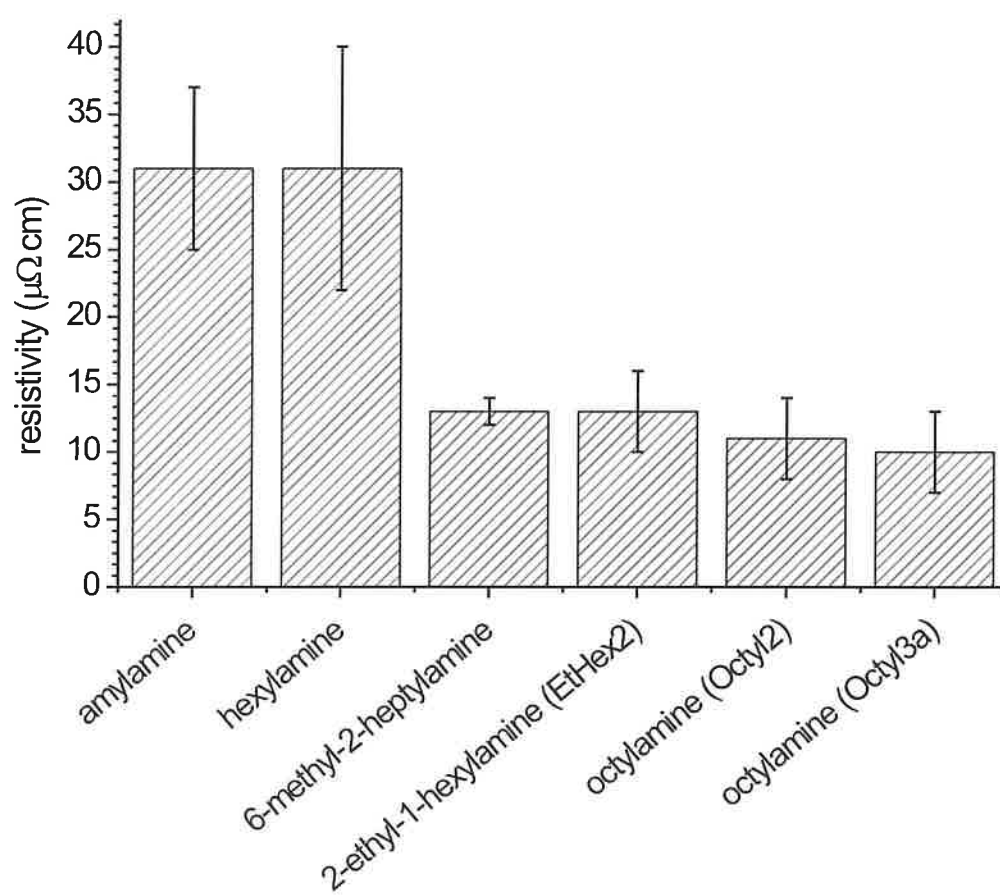


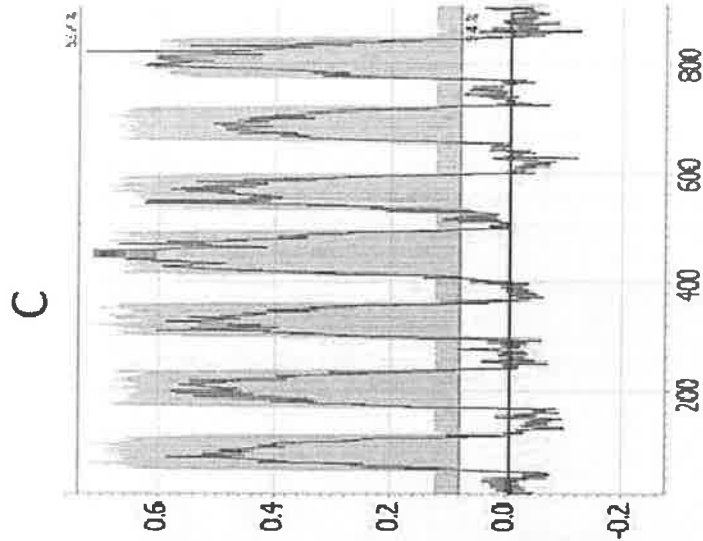
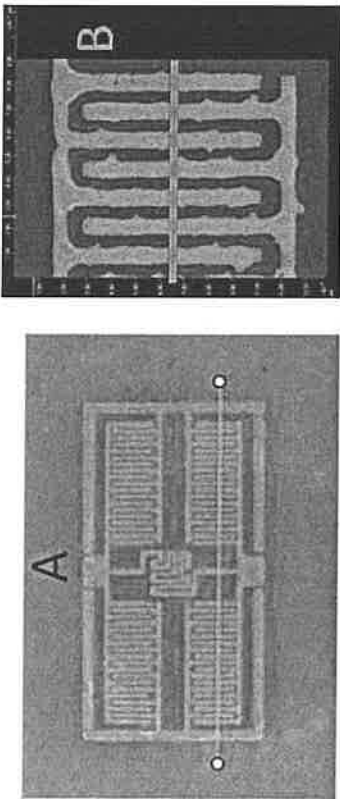
Fig. 3

Properties of Conductive Traces Made From Silver-based Molecular Inks

Ink	composition					Sheet resistivity (mΩ/□/mil)		Resolution		Thickness (μm)	Surface roughness				Mechanical		Printability (# print cycles before thinning/cleaning of screen required)
	Ag salt (%)	Ethyl cellulose (%)	Solvent 1 (%)	Solvent 2 (%)	Solvent 3 (%)			Nominal Line Width (mil)	Measured (mil)		R _a	R _q	R _t	R _z	Flex	Crease	
E11 (NRC-2)	50	5	Xylene (39.5)	Terpineol (5.5)	-	5		2.0	3.3 (Δ=0.7)	0.48	0.02	0.03	0.31	0.19	R increase < 10%	R increase < 10%	4-6
E12 (NRC-4)	50	3.6	Tetralin (45.4)	-	-	7		2.0	4.1 (Δ=1.0)	0.42	0.02	0.03	0.36	0.22	R increase < 10%	R increase < 10%	>20
E13 (NRC-5)	50	4	Mesitylene (37)	Tetralin (9)		4		2.0	3.7 (Δ=0.8)	0.50	0.04	0.06	0.31	0.23	R increase < 10%	R increase < 10%	10-15
E14 (NRC-7)	50	5	Xylene (19.75)	Terpineol (2.75)	Diethylbenzene (22.5)	5		2.4	3.4 (Δ=0.5)	0.52	0.03	0.04	0.39	0.24	R increase < 10%	R increase < 10%	10-15
E15 (NRC-16)	50	4	Diethylbenzene (34.5)	1-octanol (11.5)	-	5		2.0	3.4 (Δ=0.7)	0.40	0.04	0.05	0.33	0.24	R increase < 10%	R increase < 10%	>20
E16 (NRC-14)	50	5	alpha-terpinene (34.5)	1-octanol (11.5)	-	6		2.0	4.3 (Δ=1.2)	0.40	0.04	0.05	0.33	0.24	R increase < 10%	R increase < 10%	>20
E17 (NRC-15)	50	5	alpha-terpinene (40)	1-octanol (5)	-	7		2.0	4.4 (Δ=1.3)	-	-	-	-	-	R increase < 10%	R increase < 10%	>10
E18 (NRC-51)	50	4	2-methylcyclohexanol (46%)	-	-	3		2.0	4.3 (Δ=1.2)	-	-	-	-	-	R increase < 10%	R increase < 10%	>20

Fig. 4

EX-14
(NRC-7)



ink	Linewidth nominal (mil)	Linewidth measured (mil)	Line spacing nominal (mil)	Line spacing measured (mil)
NRC-7	2.4	3.4 ± 0.2	2.4	1.4 ± 0.2

Fig. 5

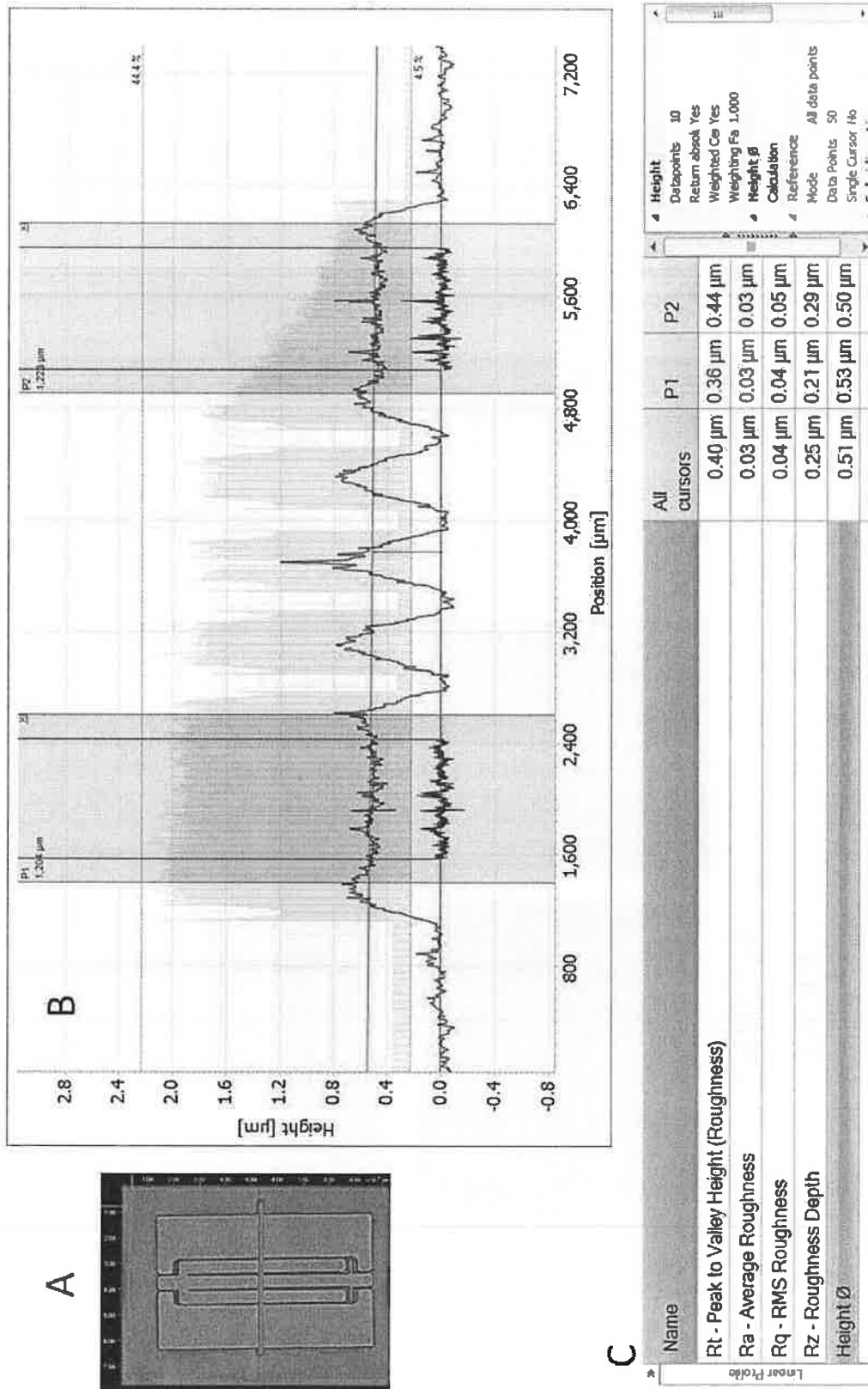


Fig. 6

Ink type	Substrate	Trace thickness (μm)	Nominal Trace width on film (mil)	Resistivity ($\text{m}\Omega/\text{sq}/\text{mil}$)	Flex test ASTM (R increase in %)	Crease test ASTM (R increase in %)	Current carrying capacity ASTM (mA)	Silver migration ASTM
NRC-2	Polyimide	0.6-0.9	5	3.8	2.2	0.56	186	PASS
			10	3.7	1.5	0.69	259	
Henkel 725A	PET	12-16	5	17	0.39	0.36	161	PASS
			10	12	0.54	0.82	225	
Henkel 725A	Polyimide	12-16	5	23	0.9	3.21	598	PASS
			10	23	1.65	3.25	523	

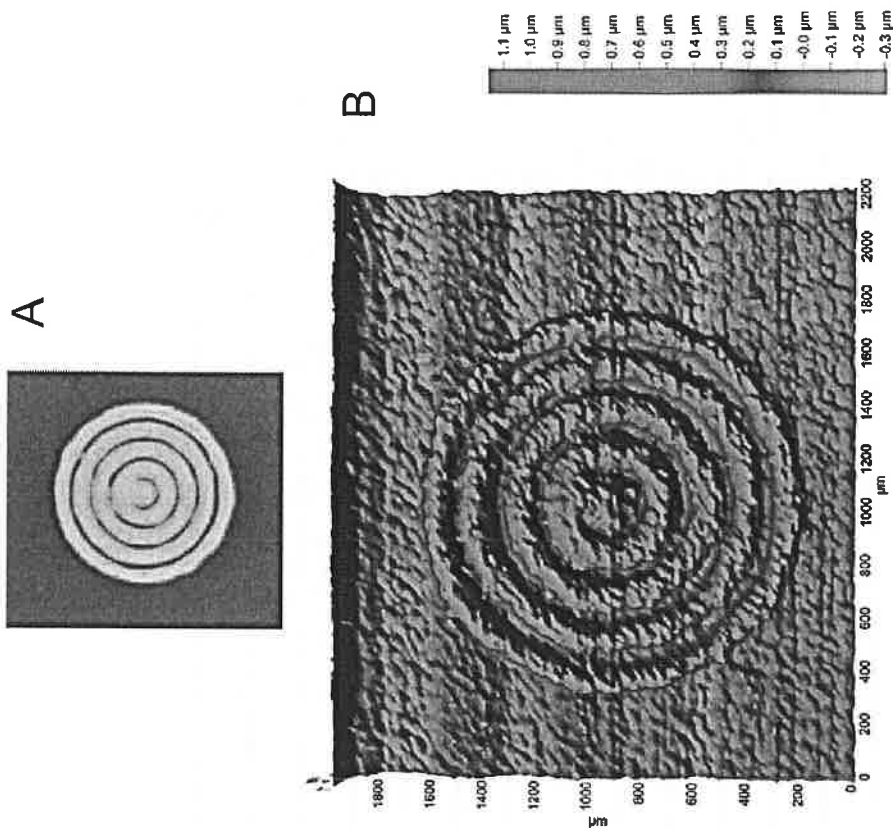
Fig. 7

Nominal linewidth (mil)	2	3	5	10	15	20
Ω	329	244	175	106	80	63
Length (μm)	1.00E+05	1.00E+05	1.00E+05	1.00E+05	1.00E+05	1.00E+05
Linewidth (mil)	6.60	7.16	9.08	13.40	19.00	23.50
Δ (mil)	2.30	2.08	2.04	1.70	2.00	1.75
Linewidth (μm)	167.64	181.86	230.63	340.36	482.60	596.90
# of $\square$	597	550	434	294	207	168
$\Omega/\square$	0.55	0.44	0.40	0.36	0.39	0.38
m $\Omega/\square$	552	444	404	361	386	376
Line thickness (μm)	0.55	0.62	0.90	1.29	1.16	0.88
Thickness (mil)	2.2E-02	2.4E-02	3.5E-02	5.1E-02	4.6E-02	3.5E-02
Sheet resistivity (m $\Omega/\square$ /mil)	11.94	10.83	14.30	18.32	17.63	13.03
Volume resistivity ($\mu\Omega\cdot\text{cm}$)	30.3	27.5	36.3	46.5	44.8	33.1

Fig. 8

Nominal linewidth (mil)	10	15	20
Ω	110	112	63
Length (μm)	1.00E+05	1.00E+05	1.00E+05
Linewidth (mil)	13.60	11.93	23.40
Δ (mil)	1.80	-1.54	1.70
Linewidth (μm)	345.44	303.02	594.36
# of $\square$	289	330	168
$\Omega/\square$	0.38	0.34	0.37
m $\Omega/\square$	380	339	374
Line thickness (μm)	1.29	1.16	0.88
Thickness (mil)	5.1E-02	4.6E-02	3.5E-02
Sheet resistivity (m $\Omega/\square/\text{mil}$)	19.3	15.5	13.0
Volume resistivity ($\mu\Omega\cdot\text{cm}$)	49.0	39.4	33.0

Fig. 9



E17 (NRC-15)		
	Linewidth (mil)	Line spacing (mil)
Nominal	2	4
measured	4.6	1.4
Δ (difference between nominal and measured linewidth)	1.3	-

Fig. 10