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1. Introduction

Metallic nanowires (NWs) have been marked as a promising material for transparent conductors (TCs) for a variety of optoelectronic, photovoltaic¹ and nascent applications that demand mechanical flexibility.² In particular, copper and silver NWs have been the metals of choice due to their high conductivity, amenability towards solution synthesis and inherent mechanical flexibility. Cu has the added advantage of being relatively abundant and considerably cheaper than silver, making it economically attractive for applications where TCs are required in large quantities.

However, the endeavour to employ Cu NWs in an environmentally and commercially sustainable fashion faces many challenges. These include the need for large-scale green synthetic routes, the ability to control the NW dimensions and their dispersibility in solvents. Thereafter one must be able to deposit the NWs onto a variety of substrates, preferably with

Facile control of copper nanowire dimensions *via* the Maillard reaction: using food chemistry for fabricating large-scale transparent flexible conductors[†]

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Solution-grown copper nanowires (Cu NWs) are promising substitutes for vacuum deposited transparent conducting oxide films. Here, we shed new light on the synthetic chemistry of Cu NWs, showing that their formation can occur as part of Maillard's reaction, a reaction more commonly associated with food chemistry. With this newfound understanding, we adopted a generalized approach which led us to the use of non-toxic amino acids, hydrophobic amines and glucose to synthesize Cu NWs of tunable aspect ratios. The ability to tune the aspect ratio is rarely reported, and is critical in preventing the NWs from getting entangled. Consequently, we demonstrate that the well-dispersed Cu NWs could be deposited to fabricate flexible transparent conductors (TCs) on virtually any substrate, even superhydrophobic surfaces. The chemistry studied here has allowed us to circumvent prevailing methods that use hazardous hydrazine and ethylenediamine as reagents, thus opening up a new synthetic pathway towards obtaining metal NWs in an environmentally sustainable fashion.

minimal use of binders and surfactants. Subsequently, one has to be able to decrease the inter-NW junction resistance, and ensure long-term stability against oxidation through various passivation techniques.^{3,4} Ideally, all these have to be tackled without the use of high temperature processes, vacuum steps or hydrogen. Clearly, the successful incorporation of Cu NWs with prevailing technologies requires an integrated approach that is able to meet the aforementioned requirements in a non-conflicting and cost-effective manner. We believe that such an approach always starts with understanding the possibilities and limitations of various synthetic routes.

The synthesis step holds the key to achieving the desired NW dimensions, which in turn determines the electrical and optical properties of Cu NW TCs. It has been established that thin (<20 nm) nanowires interact minimally with light, while thicker nanowires provide better conductance–extinction ratios.⁵ Long nanowires, on the other hand, are able to form more junctions than short nanowires, thus improving the connectivity of a meshed network of NWs. Hsu *et al.* demonstrated that a combination of mesoscale copper lines of (5 μ m diameter, 100–500 μ m spacing) and copper nanolines could give optical transparencies >90% and sheet resistances of less than 1 Ω sq⁻¹.⁶ The rationale was that low density mesoscale copper lines provided a long distance and low resistance pathway for charge transport without significantly impeding the optical transmission. The complex structures in the mentioned work

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were fabricated separately using electron beam lithography and a combination of electrospinning-metal evaporation steps. While these studies have investigated how NW dimensions influence the TC performance, such efforts must be matched with the practical ability to control the dimensions of Cu NWs. Such a capability is yet to be demonstrated for Cu NWs.

To date, many synthesis methods have been reported using different precursors and conditions. Regardless of the method, the unifying principle involves the reduction of Cu ions in a solution to its metallic state in the presence of a capping agent which encourages 1-dimensional growth. Zeng et al. employed hydrazine to reduce Cu²⁺ with a combination of ethylenediamine (EDA) and NaOH to foster 1D growth. Cu nanowires of 40-50 µm and 100 nm diameters were obtained.⁷ Using the same method, Wiley et al. were able to functionalize the Cu NWs into TCs on polyethylene terephthalate (PET) by a membrane transfer method.8 Later, the same authors were able to achieve roll-to-roll (R2R) deposition using a coating rod by incorporating the Cu NWs into an ink formulation.⁹ To the best of our knowledge, we notice that only groups which employed the hydrazine/EDA combination were able to employ R2R deposition techniques.

Other groups have avoided the use of hydrazine and EDA, and have instead studied Cu NW synthesis using (relatively safer) long carbon chain amines in water. For instance, using an aqueous suspension of CuCl₂ and octadecylamine (ODA), Huang et al. were able to obtain a dense mesh of Cu NWs after 48 h of heating at 180 °C.¹⁰ Here, ODA played the dual role as the capping and reducing agents. More recently, Jin et al. used glucose to reduce Cu²⁺ with hexadecylamine (HDA) as a capping agent at 100 °C in an aqueous solvent.¹¹ The benefits of this approach are the exclusion of hazardous chemicals and the relatively low synthesis temperature that does not necessitate the use of autoclaves. The authors claimed that NW lengths of several millimeters and diameters of about 24 nm were obtained. However, in our preliminary work,¹² we found that such high aspect ratios always gave the NWs a high degree of flexibility that caused them to become irreversibly entangled, ultimately making it impossible to obtain well dispersed suspensions even after sonication. Moreover, the use of hydrophobic HDA within an aqueous solvent aggravated the problems of NW agglomeration and entanglement. Therefore, despite the advantages of using long carbon chain amines over toxic hydrazine and EDA, the trend remains that the resulting NWs possess extremely high aspect ratios and thus do not permit the formation of stable suspensions. Hence, there remains a need to be able to achieve these aspect ratios without having to use hazardous reagents.

In this work, we re-approach the above synthesis route proposed by Jin *et al.* with new experimental evidence that clarifies the roles of the respective reagents while providing mechanistic insight into the synthesis.¹¹ This opens up new possibilities towards the reduction of metal cations for NW synthesis *via* the Maillard reaction – a reaction involving sugars and amines commonly studied in food chemistry. Most importantly, we demonstrate that the addition of glycine enables us to exercise unprecedented control over the NW dimensions. Through the simple addition of glycine, we were able to tune the length from several millimeters to the sub-100 µm regime, while simultaneously increasing the diameters to about 150 nm. By decreasing the aspect ratio, the NWs were found to be stiffer and less susceptible to getting tangled during synthesis, producing excellent NW dispersions. The stable Cu NW dispersions enabled us to perform large-scale deposition of Cu NWs using an airbrush. Cu NWs were deposited on rigid, curved and flexible substrates, and were often immediately found to be conducting without the need for any post processing steps.

2. Experimental

Materials

All materials and chemicals were used as acquired without further purification. 1-Hexadecylamine (HDA, Alfa Aesar), glycine (VWR), trichloroacetic acid (Tokyo Chemicals Industries), anhydrous copper chloride (Aldrich), D-(+)-glucose (Aldrich), potassium ferricyanide (Aldrich), iron(m) chloride (Aldrich), sodium phosphate monobasic (Aldrich), sodium phosphate dibasic (Aldrich), and polyvinylpyrrolidone (Mwt. 10 000, Aldrich) were used without further purification.

Synthesis of Cu NWs

In a standard recipe, 30 mg of anhydrous copper chloride was added to 10 ml of deionized water. 0.18 g of HDA was then added and sonicated with an ultrasonic probe for 3 min until a light blue emulsion was formed. 0.05 g of glucose was then added and the emulsion was left to stir for 10 min at 50 °C. Thereafter, the bottle was capped and placed in a pre-heated oven at 102 °C for 6 hours. The NWs were then rinsed with ethanol and centrifuged 4 times (1 min, 2000 rpm) until the supernatant turned clear. 10% PVP (Mwt. 10 000) was added if the NWs were to be kept for prolonged periods of time to retard the oxidation of Cu.

Reducing strength assay

Samples of HDA and/or glucose were prepared without $CuCl_2$ and placed in a pre-heated oven at 102 °C. 100 µl of each sample was drawn at 30 min intervals to measure the reducing strength. Each 100 µl sample was mixed with 2 ml of phosphate buffer (pH 6.6, 0.1 M) and 1 ml of aqueous 1% K₃Fe-(CN)₆. The solution was left to stand in a 50 °C water bath for 15 min to allow the reducing agents to reduce the ferricyanide to its ferrous cyanide. Thereafter, 1 ml of 10% trichloroacetic acid was added, and the solution was centrifuged at 4000 rpm for 1 min. 1 ml of the supernatant was then diluted with 1 ml of deionized water and 200 µl of 0.1% FeCl₃ to form the Prussian blue complex.

Airbrush deposition

Cu NWs were suspended in ethanol during airbrush deposition. Before the deposition, 100 μ l of 1% hydrochloric acid (in ethanol) was added to the Cu NW suspension and stirred for 5 min to remove any surface oxide layer. The NWs were then centrifuged once (1 min, 2000 rpm) and redispersed in fresh ethanol. Thereafter, the NWs were sprayed using an airbrush (30 psi) with a nozzle–substrate distance of 15 cm. The Cu NWs were sprayed continuously for 20–50 seconds, depending on the desired coverage.

Sheet resistance study

The sheet resistance-transmission study was performed by airbrushing the NWs onto 1 cm \times 1 cm microscope glass slides. After coating, a layer of TiO₂ sol gel was spin-coated (30 s, 2000 rpm) to improve the inter-NW contact. A sol gel stock was synthesized by dissolving 0.56 g of acetylacetone, 2.61 g of titanium isopropoxide and 330 µl of deionized water into 40 ml of anhydrous 1-butanol. The sol gel was allowed to stir for 30 min before use. 1 ml of sol gel stock was diluted in 9 ml of 1-butanol and used for spin coating. The NW coverage was calculated from several SEM images of each sample. The contrast between the substrate and Cu NWs in the images allowed us to use Photoshop to count the number of pixels that belonged to the Cu NWs. The number of such pixels was then divided by the total image size to obtain the coverage.

3. Results and discussion

A standard synthesis procedure consists of blending HDA (180 mg) into an aqueous solution (10 ml) of anhydrous $CuCl_2$ (30 mg) and glucose (50 mg) using an ultrasonic probe, giving a light blue emulsion (Fig. 1A). The emulsion would then be heated at 102 °C for 6 h without stirring. The Cu NWs formed

would settle to the bottom of the vial, while the solution turned dark brown. Average yields of 40–50% were obtained. Fig. 1B shows an SEM image of tangled Cu NWs having an average diameter of 40 nm. Realistically, the NWs were too long and too entangled to be reliably determined.

To better understand the roles of HDA and glucose, variable amounts of both reagents were employed while keeping all other parameters unchanged. Vials containing different amounts of HDA (0-0.3 g) and glucose (0-0.1 g) are indicated by the 2-by-2 matrix in Fig. 1C. Those containing Cu NWs after growth are boxed in red. We first noticed that when either glucose or HDA was absent, the solution remained blue and no metallic Cu precipitates (Cu⁰) were formed. Furthermore, Cu NWs were only produced when both glucose and HDA were added in sufficient amounts. While it is known that glucose itself is able to reduce Cu²⁺ ions to Cu⁺ in Benedict's and Fehling's tests, it does not appear to be able to reduce Cu^{2+} to Cu^{0-} . Evidently, glucose alone was not functioning as the reducing agent as was originally proposed. Indeed, previous reports of Cu⁰ formation with HDA took place at significantly higher temperatures (>180 °C).¹³

In order to explain the above observations, we postulate that the Maillard reaction is responsible for the reduction of Cu^{2+} . This reaction, brought about by the reaction of an amine with a reducing sugar, is responsible for non-enzymatic browning and the characteristic aromas in cooked meats and baked bread. A general reaction scheme is shown in Fig. 2A. Briefly, the Maillard reaction starts with a nucleophilic interaction of the amine nitrogen with the carbonyl in glucose. A general amine is denoted by RNH_2 , where R represents $[-(CH_2)_{15}CH_3]$ in HDA. Condensation subsequently occurs, and after Amadori rearrangement, the glucosamine is converted to the Amadori



Fig. 1 (A) Photograph of Cu growth solutions before and after 6 h of heating at 102 °C. (B) SEM image of Cu NWs obtained from the standard recipe showing entangled portions of nanowires. (C) 2-Dimensional matrix showing the growth solutions after 6 h of growth using different combinations of glucose and HDA. Samples enclosed in the red line indicate samples that had Cu nanowires after growth.



Fig. 2 (A) A brief reaction schematic describing the formation of MRPs. (B) A reducing strength assay was performed to semi-quantitatively determine the reducing strength of different combinations of HDA and glucose. Greater the optical absorbance (measured at 700 nm) reflected, greater the reducing strength. A combination of glucose and HDA had the greatest reducing strength than either component when tested alone. (C) Time resolved transmission measurements on glucose–glycine reaction in the presence of Cu^{2+} . The corresponding growth solutions reflecting the color changes are shown in the inset.

product (N-substituted 1-amino-2-deoxy-2-ketose). According to Hodge, the Amadori product can then react *via* several parallel and sequential pathways to give a host of Maillard reaction products (MRPs) that include aldehydes, aldols and reductones.¹⁴ The MRPs can subsequently react with another amine to produce melanoidins, which are responsible for the brown colouration and antioxidizing properties of cooked food. We believe that the MRPs and melanoidins with antioxidative properties are responsible for the reduction of Cu²⁺. Such an ability has been demonstrated by reductones (such as ascorbic acid) for the formation of Cu nanoparticles.¹⁵

To determine the exact structure of MRPs and melanoidins from the reaction between HDA and glucose is beyond the scope of this publication. Indeed, it is impossible to isolate every MRP and melanoidin and test their reducing ability individually (simple models used in studying the Maillard reaction such as glucose and glycine are known to produce more than 24 compounds).¹⁶ However, by treating the reaction system as a "black box", we were able to provide a qualitative proof of Maillard's reaction by performing a reducing strength assay of the MRPs and melanoidins.¹⁷ In this assay, we measure the collective reducing strength of all the MRPs and melanoidins produced from HDA and glucose. 10 ml samples of HDA glucose mixtures were heated at the growth temperature (102 °C) to generate the MRPs, under the exact same conditions used during the standard synthesis. 100 µl of the sample mixture was then extracted (every 30 min for 3 h), and

was used to reduce a potassium ferricyanide(m) complex to its ferrous cyanide at 50 °C for 10 min in a water bath. Fe³⁺ was then added to form a complex with ferrous cyanide to form the Prussian blue complex, which could be detected by measuring the optical absorbance at 700 nm (A_{700}). Thus, a higher A_{700} was indicative of a higher reducing strength.

Since the reducing species are generated during the reaction, we expect the reducing strength, and hence A_{700} , to increase with time. Fig. 2B shows the measured A_{700} values as a function of time for different sample mixtures. Firstly, we observe that the sample containing 0.05 g of glucose (black squares) did not exhibit significant reducing properties as indicated by the consistent lack of absorbance at 700 nm (i.e. no Prussian blue was formed). We attribute this to the weak reducing nature of glucose by itself. This is consistent with our results in Fig. 1C where solutions containing only glucose remained blue. Next, the sample containing 0.18 g of HDA (blue squares) exhibited a reducing capability that was constant with time. This is consistent with the fact that HDA has a reducing power,¹⁸ albeit insufficiently powerful to bring about the reduction of Cu²⁺ to Cu⁰ at 102 °C. Its invariance with time also suggests that the concentration of HDA remained constant when heated. However, a sample containing both 0.05 g of glucose and 0.18 g of HDA (green circles) showed an A700 that increased with time. Furthermore, the measured A_{700} was significantly higher than when HDA or glucose was heated alone. This important observation shows that the reducing specie(s) is

Paper

(are) generated *in situ* as a result of a reaction between HDA and glucose. Hence, the *in situ* generation of the reducing species provides evidence of Maillard's reaction that is responsible for the reduction of copper ions. It is also worth mentioning that we consistently detect a chocolate-like aroma after synthesis, indicating the generation of volatile organic by-products – an observation that is consistent with the Maillard reaction.

In a separate experiment to validate the Maillard reaction, we substituted HDA for glycine. Glucose-glycine systems have been extensively studied as models for the Maillard reaction. An added benefit was that glucose-glycine solutions were transparent, as opposed to suspensions containing HDA. This allowed for the performance of time-resolved absorbance measurements that reflected the evolution of the Maillard reaction. At intermediate stages of the reaction, it is known that the MRPs exhibit strong absorption in the UV region due to the formation of conjugated molecules.14,19 As the reaction proceeds further, the solution turns brown due to melanoidin formation, which comprises highly conjugated nitrogenous polymers. The overall trend is a red shift in the absorbance edge starting from UV wavelengths. By observing the absorbance spectra at various time intervals in Fig. 2C, this trend was empirically observed in glucose-glycine systems (0.5 g glucose, 0.5 g glycine, and 0.03 g of CuCl₂ were dissolved in 10 ml of deionized water and heated to 102 °C). Prior to heating (0 min), the solution appeared deep blue due to the formation of the copper-glycinate complex, as reflected by the absorption maximum at 650 nm. After 30 min, a notable decrease in transmission in the near-UV (300-400 nm) was observed due to the formation of MRPs. From 60-120 min, the absorption edge gradually red-shifted as more MRPs and melanoidins were formed. Incidentally, absorption at 650 nm continually decreased due to the conversion of the Cu²⁺ to Cu⁰. The first signs of Cu crystals were visible after 90 min. These crystals comprised mixtures of irregularly shaped Cu nanoparticles and nanowires (see ESI[†] Fig. S1). We note that the browning in the solution was due to the presence of melanoidins and not the presence of Cu⁰. In summary, this experiment confirmed the time-evolution of the optical absorbance expected of Maillard's reaction.

From both these studies, it is clear that the roles of HDA and glucose cannot be simply ascribed to that of a capping and a reducing agent respectively. This realization of Maillard's reaction led us to investigate the use of other combinations of amines together in order to synthesize Cu nanocrystals of different morphologies. Surprisingly, we found that by using a combination of HDA and glycine as the amine sources (together with glucose), we could achieve remarkable control over the NW lengths and diameters.

Fig. 3A shows the lengths and diameters that could be obtained by adding a variable mass of glycine (5–100 mg) to a standard recipe. We observed a general decrease in NW lengths from about 100 μ m to 25 μ m as the amount of glycine was increased from 5 mg to 100 mg. (XRD and EDX analyses of the samples grown with glycine confirm that the products were metallic copper as shown in ESI† Fig. S2.) Interestingly, the distribution in NW lengths appears to become narrower



Fig. 3 (A) NW length (red squares) and diameter (blue circles) as a function of the mass of glycine used, showing how glycine can be used to tune the NW aspect ratio. SEM images of the corresponding nanowires are shown containing (B) 10 mg, (C) 25 mg, (D) 100 mg of glycine.

with increasing glycine amount. Concomitantly, NW diameters increased almost linearly from 55 nm to 150 nm, significantly reducing the NW aspect ratio. Fig. 3B–D shows SEM images of Cu NWs grown with 10, 25 and 100 mg of glycine, with the variation in NW lengths and diameters being readily apparent. It can also be easily observed that the decrease in aspect ratio imparted a degree of stiffness to the NWs as evidenced by the rigid stick-like appearance in Fig. 3D. The relatively rigid NW in Fig. 3D prevented the NWs from getting entangled.

It should be mentioned that nanoparticles of various shapes were concurrently produced. EDX confirmed that these nanoparticles were comprised of metallic copper (see ESI† Fig. S3). The morphology of the Cu crystal depends on the shape and nature of the seed crystal. It is known that metallic nanorods or nanowires originate from multiply-twinned decahedral seeds that elongate in the <111> direction to minimize strain energy.20 On the other hand, nanoparticles originate from single-crystal polyhedral seeds. Both types of seeds will be present in a typical synthesis, and so both NWs and particles would be present. However, the relative amounts of each type of seed can be manipulated. Jin et al. suggested that the addition of HDA suppresses the oxidative etching of multiplytwinned seeds, resulting in relatively more NWs.¹¹ In our work, we did not attempt to further suppress the formation of particles, as the ratio of NWs to nanoparticles was sufficiently high for transparent conducting substrates.

Several possible reasons exist to explain the apparent change in NW morphology. Firstly, glycine reduces the amount of HDA that bonds to the surface of the Cu NW. This is achieved through competitive adsorption of glycine on the nascent Cu surfaces during growth through its amine and carboxylic acid groups.²¹ Due to its relatively shorter carbon chain, glycine is less effective as a capping agent than HDA, resulting in NWs of larger diameters. Secondly, the carboxylic group of glycine also deprotonates to form a salt with the amine group on HDA, thereby limiting the HDA absorption onto Cu as more glycine is added. Lastly, glycine itself participates in the Maillard reaction which further increases the reducing strength of the system (see ESI† Fig. S4). Higher reducing strength gives rise to higher supersaturation of Cu⁰ seeds with better size uniformity. This ultimately produces shorter NWs with a decreasing length distribution on the addition of more glycine. In this work, the addition of 0.1 g of glycine consistently produced NWs that were 24(±5) µm long with average diameters of 145(±20) nm. NWs on this length scale were easy to disperse in ethanol without getting tangled, thus enabling the formation of well-dispersed suspensions without the need for hydrazine or EDA.

In order to demonstrate R2R capability, we opted to use an airbrush to deposit the Cu NWs to make functional TCs. We highlight two benefits of this approach: firstly, even and controllable NW coatings could be achieved without the use of surfactants and binders, both of which would require additional treatment steps to ensure their complete removal. Secondly, using an airbrush allows us to ignore the solvent interaction with the prospective coating surface by ensuring that the solvent evaporates before contacting the surface. Prior to deposition, as grown NWs have a native layer of Cu₂O which increases the junction resistance between NWs. This native oxide could be easily removed by stirring the NWs in hydrochloric acid before deposition as shown in the XRD spectra in ESI† Fig. S5.

Fig. 4 summarizes the extent of our current capability. In Fig. 4A, we coated the curved side of a 1000 ml Pyrex beaker, with the figure inset showing its transparency. Fig. 4B shows a flexible PET substrate coated with Cu NW in a similar manner.



Fig. 4 (A) Photograph of a 1000 ml Pyrex beaker coated with a conducting strip of Cu NWs. The inset shows the transparency of the nanowires. (B) PET substrate and (C) a hydrophobic leaf were also coated using an airbrush (contact angle measurement showing 109°, inset). (D) SEM image of the coated leaf surface showing the even distribution of Cu NWs.

The coated PET sample was stress tested by mechanical bending and was shown to be reasonably stable despite the lack of any encapsulation (see ESI† Fig. S6). Lastly, Fig. 4C shows Cu NWs deposited on a waxy leaf with a measured contact angle of 109° (inset). An SEM image of the evenly coated leaf surface is shown in Fig. 4D. We were also able to coat Cu NWs on superhydrophobic lotus leaves (see ESI† Fig. S7). However, the extreme roughness of the lotus leaf did not permit good connectivity between the NWs (resistance was of the order of $10^6 \Omega$). Nevertheless, this demonstrates that the airbrush allows for consistent and even deposition of NWs on even the most challenging of substrates.

In order to study the optical and electrical properties of the Cu NWs in TCs, the airbrush was used to deposit Cu NW of different densities on glass substrates. For comparison, Cu NWs growth with 100 mg of glycine (length: $24(\pm 5) \mu m$; diameter: $150(\pm 20)$ nm) and those grown with 5 mg of glycine (length: 97(± 22) µm; diameter: 62(± 5) nm) were used in this study. Fig. 5A shows the optical transmission (measured at 550 nm) as a function of NW density (expressed as a percentage coverage) for both types of Cu NWs. All points for both samples exhibited the same linear relation described by a line with a gradient of -0.95. With a gradient of approximately -1, this suggests that the NWs interacted with the incoming light so as to cast a geometric shadow with negligible diffraction effects, *i.e.* the transmission is nearly equal to the uncovered area of the substrate. Therefore, insofar as optical transmittance is concerned, both types of NWs give the same transmittance versus coverage relation, which is generally expected of NWs having this range of diameter. However, the thicker NWs obtained using 100 mg of glycine showed a clear improvement in sheet resistance over NWs grown with 5 mg when deposited at the same coverage (Fig. 5B). This is because while optical transmission falls linearly with diameter, electrical conduc-



Fig. 5 (A) Optical transmission (measured at 550 nm) vs. area-coverage of Cu NWs; (B) sheet resistance vs. area-coverage; (C) transmission vs. sheet resistance. All measurements here were performed on glass.

tance increases quadratically. Fig. 5C shows the transmission sheet resistance relation of the two NW types, showing that sheet resistances of 10–15 Ω sq⁻¹ can be easily realized with about 80% transmission.

4. Conclusion

In summary, we have synthesized highly dispersible Cu NWs using a combination of HDA, glycine and glucose in an aqueous solvent at low temperatures. We provided compelling evidence that the reducing agent(s) are generated in solution via Maillard's reaction, as shown by a time-resolved reducing strength assay. As such, our findings showed that both reducing sugar and amines were needed in sufficient amounts to bring about the desired reduction of Cu²⁺. With this understanding, we were motivated to investigate the use of different amine-containing molecules in an effort to achieve other Cu crystal morphologies. A combination of HDA and glycine was shown to be able to systematically shorten the Cu NW lengths from the millimeter range to about 24 µm, while diameters could be simultaneously increased from 55 to 150 nm. This drastic decrease in the aspect ratio prevented the NWs from getting irreversibly entangled, enabling the formation of welldispersed Cu NW suspensions without the need for additional binders or surfactants. The Cu NWs were deposited onto various substrates by means of an airbrush. By ensuring that the solvent had evaporated before contacting the substrate, solvent-substrate interactions could be neglected, allowing us to coat a variety of substrates, even hydrophobic surfaces, without any prior treatment. Lastly, we showed that Cu NWs grown with glycine, with 150 nm diameters and improved dispersibility, provided a superior combination of optical transparency and sheet resistance. As such, this study provides a preliminary step towards the scalable and "green" synthesis of Cu NWs that will meet the many challenges of flexible TC design.

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