PAPER

Strongly adhesive and flexible transparent silver nanowire conductive films fabricated with a high-intensity pulsed light technique†

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Large-scale silver nanowire (AgNW) mesh films have received increasing attention as new transparent conductive films used in various printed devices. However, there are two crucial issues in implementing AgNWs that need to be addressed: (1) strong adhesion between AgNW film and substrate and (2) high conductivity with short treatment time for low-cost printed technology. Here, a high-intensity pulsed light (HIPL) sintering technique, which provides extreme heating locally in the AgNW film and at the interface between the film and polymer substrate, sinters the AgNW film to produce high conductivity with strong adhesion on the substrate. Importantly, light intensity, exposure time, and AgNW amount can be adjusted simply to form films that meet specific device needs. A flexible AgNW film with sheet resistance of 19 Ω sq^{-1} and transmittance of 83% at 550 nm is obtained with only one-step on a polyethylene terephthalate substrate with a light intensity of 1.14 J cm^{-2} under an exposure time of only 50 μs. The film can endure multiple peeling tests, which will play an important role in printed electronics.

1. Introduction

With the rapid market expansion of smartphones and tablets, an industrial demand for low-cost, flexible, and transparent conductive films, instead of expensive and brittle ITO-sputtered films, has stimulated and expedited the development of transparent conductive materials. For example, carbon nanotubes, graphene, metal grids, thin metal films, and silver nanowire (AgNW) mesh films have been developed so far. Among these materials, AgNW mesh films with excellent electrical conductivity and stability have attracted the most attention and have been used in various electric devices.[1–12] Importantly, AgNWs can be dispersed in ink and printed by the roll-to-roll (R2R) low-cost solution processing, which is an appealing next-generation manufacturing technique for forming electronic devices on flexible substrate materials with a large area. The formation process of AgNW transparent films meets these printing conditions through the development of a drop-coating[8,10] or Mayer rod coating[3,22] method to achieve touch screens,[10] organic solar cells,[4–7] and organic light-emitting diode[11,12] devices. AgNW transparent films are expected to play a significant role in printed electronics.

However, several issues need to be addressed for the wide application of AgNW films in printed electronics. First, strong adhesion between AgNW film and substrate is necessary. The need to improve the adhesion has been addressed by modifying the substrate surface,[2,13] applying strong conformal pressure,[2,5–8] using *in situ* polymerization,[11,12] and encapsulating the surface.[3] These methods have complicated the process by lengthening processing time and have even damaged AgNW films, thereby limiting the use of AgNW films in some fields.

Another problem is that high conductivity must be achieved as quickly as possible to match the rapid R2R production lines. Because the AgNW surface is coated with polyvinylpyrrolidone (PVP) during synthesis and solution dispersion for film preparation, huge contact resistance can develop between wires, requiring extra treatments to fuse the crossed AgNWs together to ensure high conductivity. These treatments include high-temperature (over 150 °C) or long-duration thermal annealing,[1,2,4] applying extra pressure,[2,5–8] an oxide-assisted method,[9] *etc.* There were problems reported for these treatments: the high-temperature process inhibited the application in flexible heat-sensitive polymer substrates; the high-pressure technique caused some damage to brittle substrates and devices; and the oxide-assisted method introduced some impurities into pure Ag films. Moreover, all these methods are time-consuming and multi-step complex for rapid printing production lines.

Recently, light-induced heating of materials has been studied in an effort to develop and control biochemical reactions, manipulate the precise growth of nanostructures, and improve solar thermal energy conversion and rapid sintering of metal

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materials. In particular, intense pulsed light with a broad spectrum in the visible range has attracted substantial attention for sintering of metal nanoparticles at a low temperature, fast speed, and on large-scale areas.[14–20]

In contrast to the conventional thermal sintering technique in which the sample is exposed continuously to high-temperatures, the photonic sintering technique irradiates the sample with multiple short flashes, each with a pulse length in the range of a few microseconds to milliseconds.[14–20] The photonic sintering used mainly on metal films has a higher absorbance of radiant lamp energy, which results in a faster rise of temperature of the metal film needed for sintering. Recently, light-induced welding of AgNWs into large interconnected networks has been described, mentioning that the treatment prevented substrate damage due to the very short treatment.[14] Other reports have also suggested that the adhesive between film and substrate had been improved but no detailed information was provided in the given reports.[15–20] We consider the interface between the metal and polymer substrates that will be activated due to the heat coming from the irradiated energy which can only be absorbed by metal and not non-metal polymer substrates. Combining the heating properties of metal and polymer substrates, in one-step, achievement of high conductivity and strong adhesion of AgNW conductive films will be possible by controlling and trailing the interface heating (i.e., irradiation time and energy).

In the present study, we developed a high-intensity pulsed light (HIPL) sintering technique to form strongly adhesive and large-area AgNW transparent mesh films under ambient conditions with only tens of microsecond treatment. AgNWs prepared with a polyol process were coated on a polyethylene terephthalate (PET) substrate and sintered using a Xenon strobe lamp system under varying levels of light intensity and pulse time. The resulting adhesion, transparency, and sheet resistance of the films were measured, and the film microstructures were examined by scanning electron microscopy (SEM).

2.   Experiment and methods

Preparation of Ag nanowires and films

AgNWs were synthesized by the polyol process, as previously reported.[8,21] Briefly, 0.98 g of PVP (average molecular weight of 360k in terms of monomeric units) was slowly added to 125 g of ethylene glycol for dissolution, and then 1.08 g AgNO$_3$ was added to form a uniform solution at room temperature. After 16 g of an FeCl$_3$ solution (6×10^{-4} mol L^{-1}, in ethylene glycol) was dumped into the mixture solution, the solution was immediately put in a pre-heating reactor to grow Ag nanowires at 150 °C for 1.5 h. Then, the silver-colored suspension was cooled to room temperature. First, the nanowires were precipitated with a large amount of acetone because PVP covering the surface of nanowires cannot dissolve in acetone. Next, the nanowire precipitate was washed with ethanol by centrifugation at 5000 rpm for 10 min. The process removed the ethylene glycol and excess PVP depending on the washing times. At last, the nanowires were redispersed in ethanol for further use. The AgNWs were drop-coated or Mayer-coated on PET films and then dried at 60 °C for 1–2 min to form uniform AgNW films with a size of 5 cm × 5 cm square area, which were sintered with high-intensity strobe light

(PulseForge 3300, Novacentrix, Austin, TX, USA)[23] by adjusting the light intensity and exposure time. The sintering process was performed under ambient conditions. The image of a sintering system is shown in Fig. S1 (see ESI†).

Optical, electrical, and microscopic characterization

Transmittance spectra were taken with a Jasco UV-visible-near infrared spectrophotometer (V670, JASCO Corp.) with the original PET substrate as a reference. The sheet resistances of electrodes were measured using the four-probe method with a surface resistivity meter (LorestaGP T610, Mitsubishi Chemical Analytech Co. Ltd.) which was directly touched on the center part of the AgNW film. The adhesive test was done as follows: an adhesive tape (3M, USA) was firmly pressed onto the AgNW films and then slowly peeled off from the films. The process was repeated several times to evaluate the adhesion property of the AgNW films by measurement of sheet resistances. SEM images were taken on a JEOL JSM-6700F electron microscope with an accelerating voltage of 15.0 kV. The bending test was performed as follows: the AgNW electrodes on plastic substrates were fixed on a cylinder with a curvature radius of 5 mm and the AgNW film toward the convex side. The AgNW films were automatically and repeatedly bent from a plane to 90° with an automatic bending apparatus (Tytron 250, MTS Systems Corporation).

3.   Results and discussion

It is known that AgNW films fabricated with pressure or normal heat treatment can be easily peeled off from the substrate with an adhesive tape because there is no interaction between the metal Ag and the polymer or glass substrates. To improve the interconnection without adding other elements, the interface between metal Ag and polymer substrates is important and should be designed by considering interface heating with the HIPL treatment. The heat generated by metal-absorbing irradiated energy is always transferred to substrates, i.e., to the interface between the metal film and substrates. Controlling and trailing the interface heating are expected to improve the adhesion between the metal film and polymer substrate by utilizing the completely distinct heat properties of the polymer substrate and metal film. These results have been confirmed by the HIPL treatment in the present work.

In this study, AgNWs prepared according to previous reports[8,21] are coated on a PET substrate by a drop-coating[8,10] or Mayer rod coating[3,22] method to form AgNW films with transmittances of 82–85%. These films are treated with HIPL by adjusting the light intensity and fixing pulse durations to 50 μs unless otherwise mentioned. Fig. 1 shows the sheet resistance depending on the peeling test times with varying light intensities. The adhesive tape (3M, USA) was firmly pressed onto the AgNW films and then slowly peeled off from the films by hand. At low light intensities, these films could not withstand the peeling test and immediately failed with light intensities of 0.21 and 0.43 J cm^{-2}, respectively (Fig. 1). It is very interesting to discover that the tape changed into a conductor after the peeling test, which indicates that the AgNW films have been completely transferred to the tape side. When the intensity is increased to 0.739 J cm^{-2}, the sheet resistance is slightly increased for the first
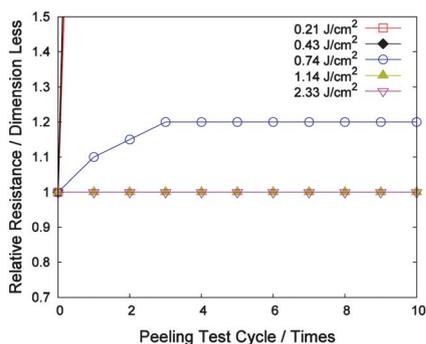
Fig. 1 Variations in sheet resistance of AgNW films as a function of peeling cycles.

three peeling cycles. After that, the sheet resistance does not change. By further increasing the light intensity to above 1.14 J cm^{-2}, the sheet resistance remains the same even with multiple peeling tests. The result indicates that the HIPL treatment rendered excellent mechanical adhesion between the AgNW film and PET substrate by tailoring the light intensity. To the best of our knowledge, the adhesion is very strong and excellent for AgNW transparent films without any extra treatments.

On the other hand, in addition to strong adhesion, transparency and conductivity are also indispensable characteristics of AgNW films. Fig. 2 shows the transmittance spectra of AgNW films in the visible region before and after HIPL sintering under different light intensities. For the pristine AgNW film (before HIPL sintering), the film transmittance is 84.5% at 550 nm. When AgNWs are dropped on the substrate to form a film, the connections between nanowires are mainly driven by gravity, van der Waals forces between Ag nanowires, and capillary forces from solvent evaporation. Moreover, the surface of nanowires was always capped by PVP used in the synthesizing process. Hence, the connection between wires is very loose and weak, thus giving a high sheet resistance above 1 MΩ sq^{-1}.[1]

When the AgNW film is exposed to HIPL, the sheet resistances greatly reduce from above 1 MΩ sq^{-1} to only 410, 230, 30, 19 and 5.3 Ω sq^{-1}, with increasing light intensity from 0.21 to 2.33 J cm^{-2} for only 50 μs. It is very exciting to note that the film transparency is almost the same as that before the HIPL treatment with light intensities below 1.14 J cm^{-2} (inset in Fig. 2; AgNW films with transmittances of 82–85% at 550 nm have been used in the work, and no change in transparency has been
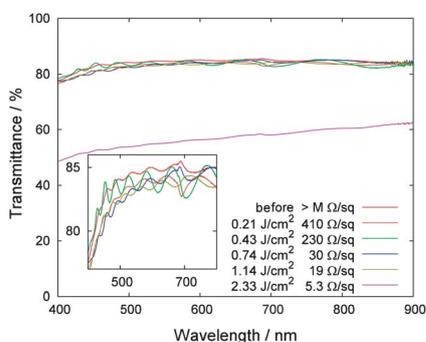
observed after the HIPL treatment with light intensities below 1.14 J cm^{-2}). However, when the sheet resistance greatly reduced to 5.3 Ω sq^{-1} with a light intensity of 2.33 J cm^{-2}, the film transparency was severely reduced to 55.06% at 550 nm. Moreover, the color of the PET substrate changed from colorless to very light brown, which is similar to that of PET substrates sintered in an oven at 200 °C for 30 min. This indicates that strong light may destroy PET substrates to decrease the transparency of PET films. PET films did not absorb the irradiated energy of the lamp. The transparency change of PET films with the HIPL treatment cannot be observed. In order to determine the effect of heat on the transparency of PET films, these films were heated at 200 °C in an oven. The results indicated that the transparency of PET films decreased from 72.5% to 55.6% at 550 nm when the PET film was heated for 60 min at 200 °C (Fig. S2, see ESI†). Hence, the reducing transparency agreed with damage of PET substrates. However, highly conductive and transparent AgNW films with strong adhesion on PET substrates have been simply fabricated with a short-duration light treatment by only a one-step process, which is very appropriate for rapid printed production lines.

Here, SEM images before and after HIPL sintering have been used to determine the reason of one-step process (Fig. 3). The charging phenomenon is always observed at the crossed positions between AgNWs from SEM images having clear shine (Fig. 3a). This indicates low conductivity due to loose connections between AgNWs.[9] Moreover, these wires show very sharp images with clear sides and corners even at crossed positions between AgNWs. The charging phenomenon drastically decreased and even disappeared after HIPL sintering with different light intensities (Fig. 3b–d), which indicated that connections between AgNWs improved with the photonic treatment, leading to decreased contact resistance between wires. It is worth noting that the surface of the wires changed from smooth to rough with changes in light intensity (Fig. 3b–d). Moreover, the sharp image became vague with many small knurls along the AgNWs, although these wires still maintained a rod-shaped morphology without any crack or break. Moreover, it is clear that the diameter and numbers of these knurls depend on the light intensity. These small dots or knurls may bind the crossed AgNWs together leading to high conductivity which has been confirmed by the sheet resistance shown in Fig. 2.

Some reports have indicated that holes and particles of sub-nanometer diameter are created on an individual metallic nanowire without disrupting the crystalline structure of nanowires with high-intensity electron beam or laser energy.[24,25] These high-intensity energies have also been used to weld metal nanoparticles, nanowires, or metal–semiconductors and remove oxide shells from crystalline nanowires by inducing rapid local surface melting and enhancing surface diffusion, in addition to local vaporization. This occurs because atomic diffusion of metals can be achieved at temperatures significantly below their melting points under certain conditions, such as ultrahigh vacuum and high energy. These studies suggest that surface melting and diffusion can only happen under special conditions. In the present HIPL sintering, these very small AgNWs have a directionally strong absorbance of the radiant lamp energy, which is expected to quickly increase the temperature on single AgNW surfaces and induce surface melting and diffusion, leading to the
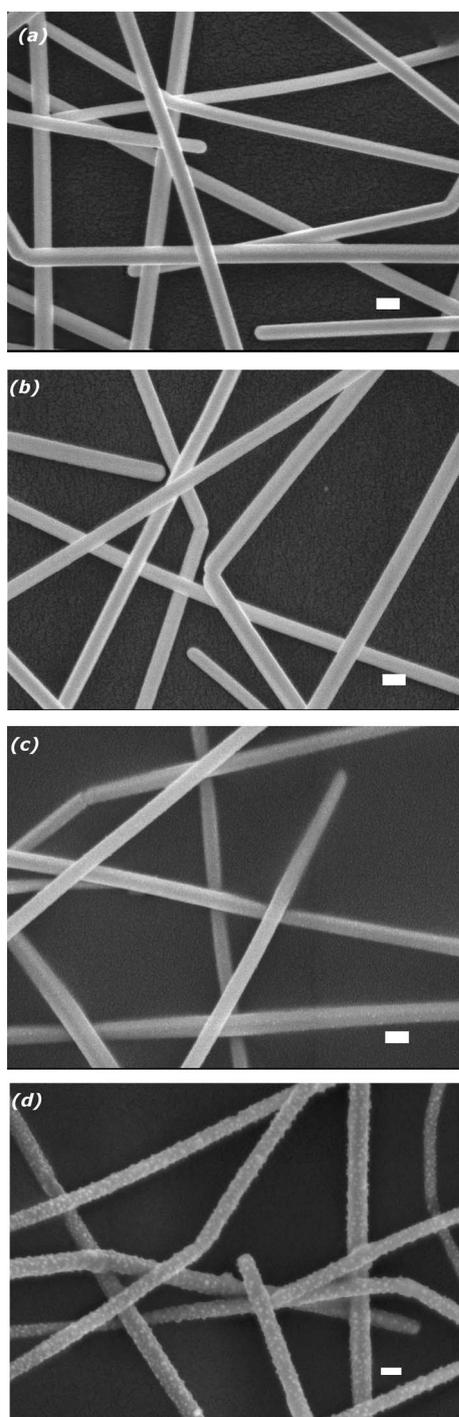

Fig. 2 Transmission spectra of AgNW films before and after HIPL sintering.

Fig. 3 Plan-view SEM images (a) before and (b–d) after HIPL sintering with light intensities of 0.21, 0.739, and 1.14 J cm^{-2}, respectively.

Fig. 4 Cross-sectional SEM images of AgNW films on PET substrates (a) before and (b and c) after HIPL sintering with light intensities of 1.14 and 2.33 J cm^{-2}, respectively.

formation of knurls. Owing to different light intensities, the speed of melting and diffusion presented the distinguishing surface states shown in Fig. 3b–d. The formation mechanism of knurls is still unclear; however, the knurls are expected to be very interesting and significant for the sintering process of AgNWs with the HIPL technique and will be further studied.

Moreover, strong adhesion between AgNW film and substrate should be related to the activated interface. Cross-sectional SEM
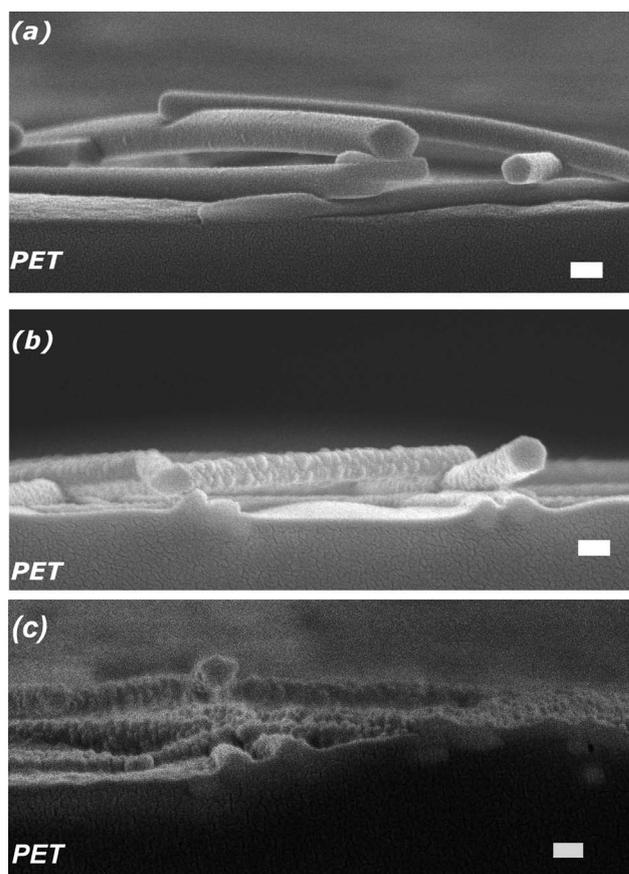
images give detailed information about the interface (Fig. 4). Before the HIPL treatment, these wires show sharp shapes and are piled up one by one on the substrate (Fig. 4a). No clear contact can be found between these wires and substrate. Hence, the AgNW film is always easily removed by hand. After the HIPL treatment with 1.14 J cm^{-2} light, some knurls were uniformly distributed around AgNWs on not only the up-side but also the down-side (Fig. 4b). These knurls, like glue, stick not only to wires all together without a clear boundary but also between wires and substrate. Moreover, it is very interesting to discover that these wires enclosed in the substrate have been partly embedded into the substrate (Fig. 4b). Although the bottom parts of these wires are embedded in the substrate, the upper parts are still exposed to air or in contact with other wires. This is the crucial reason for the high conductivity and strong film adhesion mentioned above. Although the wires are surrounded by many knurls and are tightly glued to the substrate, the original five-twin structures still remain, which implies that the melting or diffusion may have happened only on the surface of these wires (Fig. 4b).

When the light intensity was increased to 2.33 J cm^{-2}, the surface of the substrate was largely stretched and greatly deformed, and the morphology of the wires was almost destroyed with many more particles (Fig. 4c). The roughness measurement showed that the surface was much rougher than that treated with 1.14 J cm^{-2} light. The results indicate that much more energy was

maintained by the interface, which corresponds to the higher conductivity and stronger adhesion. However, serious damage to the substrate decreased the transmittance of AgNW films, as mentioned above. With an intense light, the metal will absorb much more radiant heat energy, leading to higher temperatures, which helps in achieving better sintering behavior in AgNW films and induces the interface evolution as discussed below.

The mechanism of photonic sintering is believed to be a thermal conversion of the metal precursor into its conductive counterparts, caused by the high intensity of the flash lamp.[18,19] In the present work, when a AgNW film is exposed to strong light, it absorbs the radiant energy of the lamp, which is converted into thermal energy to remove residual PVP and other impurities, further sintering the AgNW to achieve high conductivity. To investigate the sintering mechanism of the AgNW mesh film by HIPL, the temperature evolution in the film was simulated with software supplied with the HIPL equipment (Novacentrix, USA) by using some parameters, such as density, specific heat, thermal conductivity, and thickness of AgNW film and substrate PET (shown in Table S1, see ESI†). From the light intensity applied to the AgNW films, the temperature distributions in different parts (including the top layer of AgNWs, the interface between the substrate and AgNWs, and the bottom of the PET substrate) can be estimated (shown in Fig. S3 and Table S2, see ESI†). When the pulse time is fixed at 50 μs, the temperature can be immediately increased from hundreds to thousands of degrees at the top of AgNW films with 500 nm thickness. The instantaneous temperature exaltation is estimated from a dense Ag film on the substrate. In the present case, it is not a dense film but a mesh structure film with a blank area of above 80%. If 20% of the area is completely occupied by metal silver, the temperatures are about 97, 204, 351, 540 and 700 °C at the top layer of Ag with light intensities varying from 0.21 to 2.33 J cm^{-2}. The temperature at low light intensity is similar to that reported for AgNW films with a low-temperature and long-duration treatment. Hence, the same conductivity has been achieved with the rapid HIPL treatment. With an intense light, the temperatures are drastically increased to above 200 °C or even 700 °C at the top layer of Ag. The temperature of 200 °C with a light intensity of 0.43 J cm^{-2} is the normal sintering temperature for the formation of AgNW films.[1] Owing to the very short time, the sheet resistance, 230 Ω sq^{-1}, is higher than that when treated with oven sintering for more than 20 min.[1] The temperature was above 350 °C with the light intensity above 0.739 J cm^{-2}. Although for a short time, the sheet resistances drastically decreased to 30 Ω sq^{-1} and even to 5.3 Ω sq^{-1}, contributing to the high heating process.

On the other hand, apart from sintering the AgNW film, the heat can be easily and rapidly transmitted to the substrate surfaces owing to the mesh structure and high conduction of AgNWs, which have been confirmed by the simulation. The interface temperature between the AgNWs and substrate is almost the same as that at the top layer. With low-intensity light, the temperature is about 97 °C. Although this temperature is more than the glass transition temperature (GTT) for PET of about 80 °C, it seems to have no effect on the substrate due to the large ambient atmosphere. And the AgNW film is always easily removed by gentle hand friction. With a light intensity of 0.439 J cm^{-2}, the interface temperature is about 204 °C, which is far

higher than the GTT for PET and lower than the PET melting point (260 °C). This temperature can soften but not melt the substrate. Only weak adhesion can be achieved, similar to that reported with normal oven treatment.[1,2,4] Conversely, the temperatures are 350 and 540 °C with light intensities of 0.739 and 1.14 J cm^{-2}, respectively, which are higher than the PET melting point of 260 °C. Damage and deformation should have been observed in the PET, but were not observed; this may be attributed to the short duration of the heating (Fig. 4b). When thermal energy is transmitted to the interface by high-thermal-conducting Ag metal, heat can be released to the bottom-side of the substrate or can be maintained at the interface depending on the thermal conductivity of the substrate. The thermal conductivity of silver is about 420 W m^{-1} K^{-1} and only 0.24 W m^{-1} K^{-1} for the PET substrate, which is 1750 times lower than that of silver. Therefore, the heat is largely maintained at the interface. There are two routes to release the interface heating. One is to rapidly emit the heat to a large surrounding environment and another is to heat the substrate surface. Because of the enormity of the ambient atmosphere, only a part of the interface heating can affect and heat the surface of the PET substrate, avoiding damage to the substrate. However, PET has a low melting point of about 260 °C and the coefficient of thermal expansion is 9 × 10^{-2} K^{-1}, which means that PET is easily softened and even melted and expanded with heat. When the AgNW film transmitted a large amount of heat to the interface, it was expected that a part of the interface heating softened or even melted the cool surface to form a mud-like surface structure that easily buried the heavy silver metal and bonded the AgNWs on the PET surface to achieve the embedding phenomenon observed in Fig. 4b. However, because the process is very fast and short, the interface temperature can be immediately cooled down, which completes the rapid softness-solidification process without seriously damaging the substrate. The surface structure remains flat, as observed in Fig. 4b. The process greatly enhances the adhesion of AgNWs on the PET substrate. However, when the light intensity is too high, such as 2.33 J cm^{-2}, a temperature above 700 °C is obtained in the interface, which is high enough to sinter the AgNW film to give a low resistance of about 5.3 Ω sq^{-1}. It was so high that it largely deformed the substrate and created a huge pool in which these heavy AgNWs were buried, as seen in Fig. 4c. The instantaneous flowing surface may have made some AgNWs bond together, leading to a slight decrease in transmittance except the effect of the PET substrate shown in Fig. S2.† These results suggest that designing and tailoring interface heating could easily control the performance and adhesion of AgNW films on polymer substrates, which is very significant for rapid R2R processing. Finally, the bottom-side substrate temperature always remains at room temperature because PET is a poor conductor and the pulse time is very short.

At last, flexibility is also an important parameter for AgNW film use in future devices. Here, bending tests have been used to evaluate the flexibility of strongly adhesive AgNW films on PET substrates. A previous method[8] has been improved and utilized to continuously bend the film with an automatic bending apparatus (Tytron 250, MTS Systems Corporation, see ESI, Fig. S4†). The result is illustrated in Fig. 5. Similar to the case in peeling tests, flexibility in bending tests also depended on light intensity. At low intensity, the sheet resistances first decreased slightly and
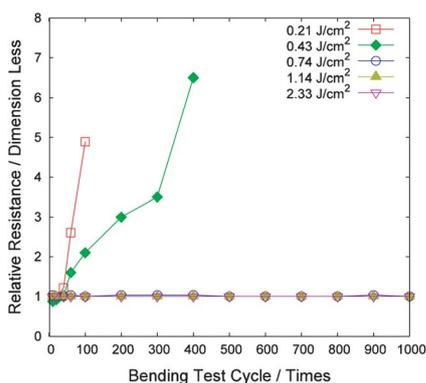
Fig. 5 Evolution of sheet resistance of AgNW films as a function of bending cycles.

Fig. 7 Sheet resistance depending on pulse time.

then gradually increased. After 200 and 500 cycles, the sheet resistances drastically increased over 5-fold with light intensities of 0.21 and 0.43 J cm^{-2}, respectively. The initial decrease in resistance may correlate with the rearrangement of AgNWs on the substrate owing to the bending force;[8] it seems that the pressure treatment enhanced the connection between AgNWs. After that, these resistances drastically increased with the cycles, suggesting that these AgNWs are destroyed or removed owing to weak adhesion on the substrates. Conversely, flexibility can be greatly improved by intense light treatment. It is notable that the AgNW film exhibits great stability with almost the same sheet resistance during 1000 cycles of a bending test, revealing a very high tolerance to bending when the light intensity is over 0.74 J cm^{-2}. Combined with the results of adhesion, this suggests that a AgNW film with strong adhesion and excellent flexibility can be fabricated on a PET substrate with the simple and fast HIPL technique, which is very crucial and important in printed electronics for high-performance devices.

As mentioned above, photonic sintering is mainly based on the metal strongly absorbing radiant energy from a lamp, leading to a faster increase in the metal film temperature and a faster completion of the sintering process. Therefore, the amount of metal on the substrate is a very important factor for the sintering process. Fig. 6 shows that sheet resistance depends on transparency, which is related to the amount of AgNWs on the substrate. High transparency means that a small amount of AgNWs is on the substrate. Here, the light intensity is fixed at 1.14 J cm^{-2} with 50 μs exposure time. It is clear that the sheet
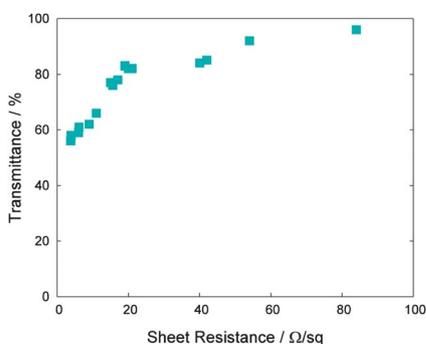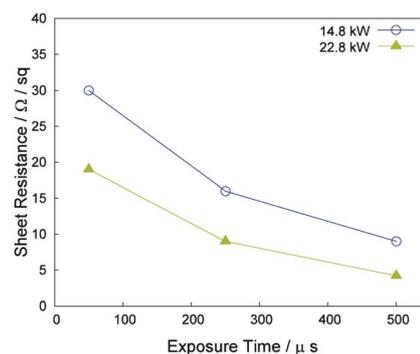
resistance has decreased with decreasing transparency, that is, with increasing amounts of AgNWs on the substrate. It can be easily understood that more metal produces more heat, which sinters the AgNW film to achieve low sheet resistance. A high transmittance film with a small amount of metal yielded low heat, which incompletely sintered the AgNW film and led to high resistance. In addition to the light intensity and the amount of metal, pulse time is also an important factor. Fig. 7 shows that sheet resistance depends on the exposure time with different light intensities. Sheet resistance always decreased with exposure time. The sheet resistances largely decreased from 19 to 6.0 Ω sq^{-1} with 500 μs exposure time under a light intensity of 1.14 J cm^{-2}. It also decreased from 30 to 9 Ω sq^{-1} with a light intensity of 0.739 J cm^{-2}. Of course, the transmittance was also largely destroyed to below 65% at 550 nm when the sheet resistance was lower than 10 Ω sq^{-1}. These results indicate that huge heating energy is retained by the metal film and that HIPL is a powerful tool for short-duration sintering. Moreover, highly transparent and strongly adhesive AgNW films can be fabricated with low light intensity and long pulse time. These results suggest that various films can be designed and tailored for various applications by adjusting the sintering parameters with the HIPL technique. The fast sintering technique will open a new window and play a major role in the production of various printed devices at a large scale.

4. Conclusion

In summary, we demonstrated a fast, optical one-step method for sintering together AgNWs by taking advantage of the extreme radiation energy offered by HIPL. The radiation heating, which locally sintered the AgNW film and simultaneously softened or even melted the interface between the film and metal, helped in achieving an AgNW mesh film with high conductivity of 19 Ω sq^{-1}, high transmittance of 83.8%, and strong adhesion (as indicated by a peeling test) under only 50 μs exposure time. The technique allows new levels of control over heat volume, generation, and transport that are probably not even possible with furnace annealing. This opens up exciting, new, simple, and large-area processes that facilitate rapid sintering of metal nanomaterials for printed electronics.

Fig. 6 Sheet resistance depending on the transmission at light intensity of 1.14 J cm^{-2}.

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