Circuit Eraser: A Tool for Iterative Design with Conductive Ink

Koya Narumi
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku,
Tokyo, Japan
narumi@akg.t.u-tokyo.ac.jp

Yoshihiro Kawahara
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku,
Tokyo, Japan
kawahara@akg.t.u-tokyo.ac.jp

Xinyang Shi
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku,
Tokyo, Japan
shixinyang@akg.t.u-tokyo.ac.jp

Shinya Shimizu
AgIC, Inc
4F Meiwa-hongo bldg.,
4-1-3, Hongo, Tokyo, Japan
shinya@agic.cc

Steve Hodges
Microsoft Research
21 Station Road,
Cambridge, CB1 2FB, UK
Steve.Hodges@microsoft.com

Tohru Asami
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku,
Tokyo, Japan
asami@akg.t.u-tokyo.ac.jp

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Abstract

Recent advances in materials science have resulted in a range of commercially viable and easy-to-use conductive inks which many practitioners are now using for the rapid design and realization of interactive circuits. Despite the ease with which hobbyists, educators and researchers can construct working circuits, a major limitation of prototyping with conductive ink is the difficulty of altering a design which has already been printed, and in particular removing areas of ink. In this paper we present Circuit Eraser, a simple yet effective tool which enables users to 'delete' existing conductive patterns. Through experimentation we have found an effective combination of materials which result in the removal of only the thin surface layer composed of ink particles, with minimal damage to the surface coating of the paper. This important characteristic ensures it is possible to re-apply conductive ink as part of an on-going design iteration. In addition to a lab-based evaluation of our Circuit Eraser which we present here, we have also used our technique in several practical applications and we illustrate one of these, namely the iterative design of a radio-frequency antenna.

Author Keywords

Rapid Prototyping; Conductive Ink; Makers; Education

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

Introduction

The use of conductive inks and pastes is becoming increasingly popular, both in the research community and also with makers and educators. This approach to circuit prototyping presents a ‘middle ground’ between the two more conventional prototyping methods of bread boarding and printed circuit board (PCB) production. It is much lower cost and lower effort than producing a PCB, but more robust, compact and repeatable than using bread boards. It supports both manual circuit creation by means of a hand-held conductive ink pen, and in the case of some inks also allows CAD based design via an inkjet printer. It is therefore accessible and versatile, allowing a range of users to sketch, annotate, cut, fold and even bind their circuits into books [9].

Despite the many advantages of conductive ink for circuit prototyping, there are some drawbacks to the approach. Firstly, the complexity of the circuits which can be created is limited by the resolution of the printing method and the single-layer nature of the process. But secondly, and perhaps more importantly, the inability to ‘undo’ circuit elements after they have been printed is a big drawback. Despite the relatively low cost of the materials concerned, it is frustrating to make a new circuit from scratch when changes are needed. In our experience, even knowledgeable electronic designers make mistakes and iterate their designs, and therefore benefit greatly from prototyping tools like breadboards which let them make alterations. This is even more important for students, where trial and error is an inevitable and important part of the learning process. Similarly, makers and designers often seek a more spontaneous and artistic way of creating circuits.

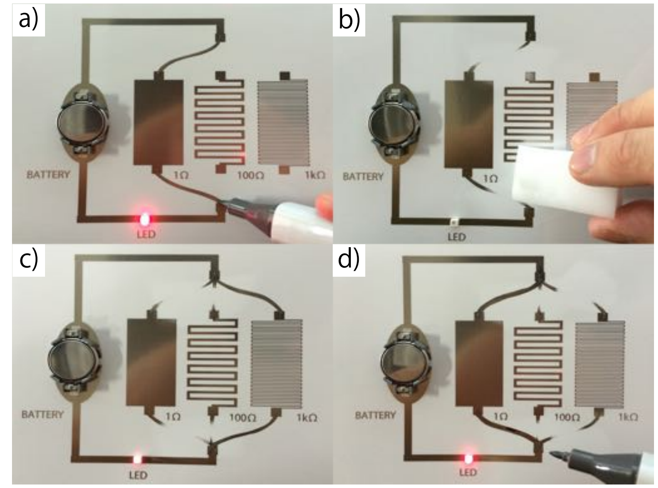

Figure 1. Circuit Eraser can be used to remove conductive patterns which are hand drawn or inkjet printed. It is possible to re-apply conductive ink in the same region if necessary.

However, to our knowledge the erasure and modification of conductive circuit patterns has not been explored. If anything, a more important factor in work to date has been ensuring that conductive inks and pastes interact with the underlying substrate in a way which produces a robust and lasting conductive structure. This is an important characteristic, but it’s essentially the opposite of what we are advocating!

In this paper we propose Circuit Eraser for conductive ink prototyping. This is a device much like a regular eraser, but which can be used to remove conductive patterns after they have been hand drawn or inkjet printed. With our approach it is possible to reapply conductive ink in the same region if necessary, and to repeat this process a number of times as shown in Figure 1.

In the remainder of this paper, we summarize related work in the area of conductive ink prototyping, we present our design goals and we compare the performance of a number of candidate solutions we have evaluated. We illustrate the utility of our Circuit Eraser in a specific application and finally conclude with an overview of future work.

RELATED WORK

Traditional electronic circuit prototyping tools

Breadboards are popular for electronics prototyping since they allow circuits to be created and modified very quickly and easily. However, they are typically quite bulky, fragile and utilitarian [4][6]. For these reasons, PCBs provide a useful alternative. They allow much more freedom with respect to the positioning of components and result in robust and compact circuits. However, PCB design, production and assembly requires time and expertise, and the resulting circuit is hard to modify [4][6].

Conductive tape, paste and ink for prototyping

As an alternative to PCB production, it is possible to create simple circuits using conductive foil tape [9]. The resulting circuits are robust, but they are limited in resolution and can be fiddly to construct.

An easier approach involves applying a conductive ink or paste; several of these suitable for electronic circuit prototyping have been developed in recent years. Carbon-based conductive paste such as Bare Paint [2] can be applied with a brush, but unfortunately is not suitable for narrow traces and small structures. It has a relatively high sheet resistance of 50 Ω/sq., making it unsuitable for many applications. Circuit Scribe [3] is a silver micro-particle paste which, like Bare Paint, can be used with a ball pen to draw circuits onto many different substrates including regular paper. Although Circuit Scribe is a convenient way to prototype circuits, the size of the silver particles is on the order of a few microns which means it cannot be inkjet printed.

We have proposed the use of self-sintering silver nanoparticle ink for circuit prototyping [1][5][6]. Unlike the silver-micro-particle and carbon-based inks above, this cannot be used with arbitrary substrates. Instead, it performs best on specially prepared surfaces such as inkjet photo paper, where a thin layer of porous material underneath a catalytic top surface causes the nanoparticle ink to sinter immediately at room temperature. But it has the advantage that ink may be applied to the substrate either by hand, using a felt pen loaded with nanoparticle ink, or with an inkjet printer. The resulting traces are robust, flexible and relatively low resistance at around 0.2 Ω/sq.

Modifying circuit configuration

Despite a number of projects exploring the application of conductive ink and paste for circuit prototyping, we are not aware of any research around the subsequent removal of ink. Olberding et al. explored the possibility of cutting and folding printed circuits to modify their shape and behavior [8], but this work didn’t consider erasing ink.

When conductive paste or ink is deposited on a hard and smooth surface such as glass or a plastic film, the trace comes off easily – in fact so easily that these substrates are not useful in practice. Instead, regular paper is often favored because its rough surface encourages the ink or paste to penetrate relatively deeply, creating a robust and reliable circuit. In this work we seek a middle ground where conductive ink

Figure 2. We evaluated 4 different materials and 6 different solvents. This is a melamine sponge soaked in alcohol.

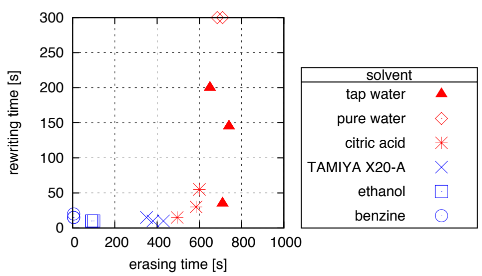

Figure 3. Erasing and rewriting time when using a melamine sponge bathed in a range of solvents.

remains robustly attached to the substrate in normal use but where it can be removed if necessary.

DESIGNING A CIRCUIT ERASER

Early design choices

Our goals for Circuit Eraser were five-fold:

1. Quick to use, taking at most a few minutes.
2. Effective; no visible stains or conductivity to remain.
3. Support re-application of conductive ink after erasure.
4. Convenient and safe to use.
5. Cheap to produce.

Having initially experimented with some of the inks and pastes described above, we quickly settled on silver nanoparticle ink as the most promising option. This is because the silver remains on top surface of the substrate in a thin 300 nm layer. This provides the opportunity for removal without significant damage to the underlying substrate or its coatings. Therefore, we used silver nanoparticle ink NBSIJ-MU01 and coated paper NB-RC-3GR120 [7] from Mitsubishi for all our experiments.

Table 1. Comparison of eraser materials, all over 3 trials.

solid material	number of rubbing	number of rewriting
tissue paper	25.6 times	1.3 times
cotton swab	27.0 times	0.7 times
urethane sponge	14.6 times	3.7 times
melamine sponge	7.9 times	2.3 times

Circuit Eraser material selection

Removal of the sintered silver layer requires the use of an abrasive material. In order to maintain the integrity of the coated substrate, and remove only the silver particles, we experimented with several kinds of light abrasives: tissue paper, cotton swab, urethane sponge and melamine sponge.

We started with 50 x 10 mm^2 strips of silver printed using the technique presented in [5]. Next, we took the material under test and briefly bathed it in water to act as a lubricant before rubbing it gently against the central 10 x 10 mm^2 area of the printed pattern. This process is shown in Figure 2. Whilst measuring the resistance of the strip we counted how many times it had been rubbed, stopping when the resistance reached 10 MΩ. When the strip had become open circuit, we then reestablished connectivity using a 7.5 mm wide felt pen containing the same ink, and counted the time taken for the resistance to drop to 100 Ω. This process of erasure and reconnection was repeated to see how many times it could be successfully performed. The results shown in Table 1 show that melamine sponge performs well, removing the silver ink more quickly than the alternative abrasives – perhaps because the surface tends to be eroded as it gets dirty. Urethane sponge is the least abrasive, supporting the greatest number of erase-then-redraw cycles, but the melamine sponge is also acceptable in this regard – we do not expect to repeatedly re-draw in exactly the same region. As a result, we decided to use melamine sponge during the rest of the experiments.

Next we compared a number of different solvents as an alternative to water. Figure 3 shows the time needed to erase a strip along with the time to re-establish conductivity for each of the different solvents. In each case we ran the experiment three times. Water consistently took the longest both for erasure and for rewriting (due to the slow drying time). As expected, the more volatile solvents ethanol and benzine supported much faster rewriting times, and they also dramatically reduced the time to erase. Although benzine has the best erasing time, it is not as off-the-shelf as ethanol and for that reason we believe that ethanol is more practical, meeting our safety requirement. When used together with a melamine sponge, we can insulate circuits over 10 MΩ/sq. within 100 sec, and make them conductive again less than 100 Ω/sq. within 10 sec. They can be erased and rewritten more than twice on average.

CIRCUIT ERASER IN PRACTICE

As described in the Introduction, we imagine our Circuit Eraser technique being useful in a number of different scenarios where circuits are being constructed and prototyped. In order to verify its potential, we decided to perform an objective evaluation in a specific application, namely ultra-high frequency (UHF) antenna design.

When designing a dipole antenna, in theory it should be a quarter of target wavelength in length. However, in reality the required length varies depending on physical properties such as the impedance of the cable, the permittivity of the substrate the antenna element is fabricated on and the properties of nearby objects such as an enclosure. Thus in practice the length of the antenna must be adjusted by trial-and-error. Using silver nanoparticle ink and Circuit Eraser, we should be able to simplify this design process.

To test this, first a dipole antenna whose element was almost equal to a quarter of the target wavelength was inkjet printed, see Figure 4.

Figure 4. This printed antenna was initially resonant at 807 MHz but was adjusted to 920 MHz using a Circuit Eraser to reduce its length. It was then re-tuned to the original resonant frequency with a conductive pen – the manually reworked areas can be seen at each end of the dipole on close inspection.

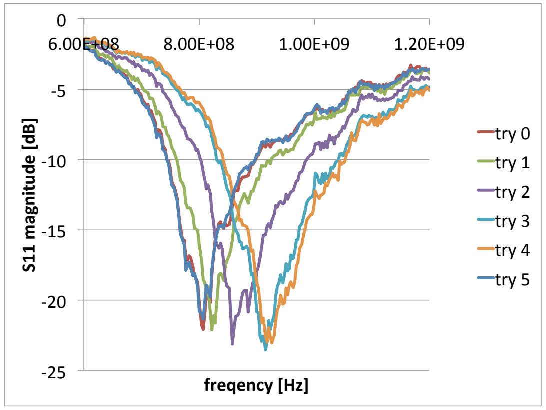

Figure 5. The resonant frequency of the printed antenna was initially 807 MHz. Following successive erasure of ink to reduce the length of the dipole (tries 1-4), it changed to the target frequency of 918 MHz. Then ink was reapplied using a pen (try 5) and resonance returned to the original frequency.

Then we connected the antenna to vector network analyzer (VNA), a machine which can measure resonant frequency. We then used Circuit Eraser and a felt pen containing silver nanoparticle ink to reduce or extend the length of the antenna elements, thereby adjusting the resonant frequency.

Figure 5 shows the results of the antenna tuning experiment. The minimum value of the S11 parameter measured by the VNA indicates resonance. Initially, the resonant frequency was 807 MHz, but following 4 cycles of erasure this had changed to the target frequency of 918 MHz. Finally we extended the antenna to return to the original resonant frequency of 807 MHz. The re-applied ink can be seen by close inspection of Figure 4.

CONCLUSIONS AND FUTURE WORK

In this short paper, we have motivated, described and evaluated Circuit Eraser, a device and technique for altering circuits created with silver nanoparticle ink. We believe it can be used to overcome one of the major limitations of prototyping and building circuits with printed conductors, namely the difficulty in fixing mistakes and iterating designs.

We have applied Circuit Eraser to a UHF antenna design task, where we found it met our design goals. We imagine it will be equally useful in other application areas and we are currently exploring some of these. In particular, our experience working with students and makers leads us to believe that Circuit Eraser will be invaluable in allowing them to fix mistakes and change their designs as they learn about circuit design. We plan to run workshops to understand better how and when the eraser can be used, and to explore a variety of industrial design options.

In addition to our own plans for future work, we hope that others will be able to replicate our success with Circuit Eraser and develop additional techniques and applications which extend the possibilities afforded by conductive ink.

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