



Flexible eWriter LC Films for Boogie Boards™

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1. INTRODUCTION

Even in today's highly digital world, pen and paper are our instruments for composing ideas; allowing the elementary process of learning to write words, drawing concepts and ideas, allowing artistic expressions, mathematics, and simply jotting down notes. Until now writing mediums have varied little through the centuries, indicating the writing feel is important, including papyrus, bark, paper, and other forms of perishable environmental resources. The need for a technique to handwrite or draw images electronically on a reusable medium is a natural progression in an environmentally conscious and technologically driven world.



Fig. 1. (On Left) A photograph of a flexible eWriter display. (On Right) A photograph of a Boogie Board Jot 8.5 that allows electronic erasing of handwritten notes.

The lightweight, relatively inexpensive, Boogie Board™ writing tablet products offer a natural writing experience with the feel of paper. No other electronic handwriting devices offer all these features at the low price points. Currently available electronic handwriting devices on the market today (tablets, smart phones with stylus input, convertible laptops, paper notebooks with smart pens) all are either fragile, heavy, expensive, or do not have the writing feel and response time.

In the flexible electronics industry, some of the first flexible displays to be commercially available are non-traditional Boogie Board eWriter displays in the unique and exciting writing tablet application (Figure 1). The Boogie Board is a pioneering device in the digital writing market space, where an image is written on the display when the user applies pressure to the top surface with either a stylus or a finger tip. It is flexible, made with rugged plastic substrates, has unique handwriting experience, and is low cost. The pressure creates a bright line on a dark background and the image can be erased with a simple voltage pulse. The Boogie Board eWriter display has a good writing response with sharp written lines.

The Boogie Board eWriter displays are based on the Kent Displays' Cholesteric Liquid Crystal Display (ChLCD).^{1,2} technology. The ChLC display technology has inherent reflective color, grayscale, and requires no power to maintain a static image. The simple structure and inherent properties of Reflex displays



make a reflective, flexible, low power display possible, which is also simple to manufacture when compared with competing technologies.

The eWriter display is built with roll-to-roll manufacturing processes and has been commercially available for over 5 years. Boogie Board eWriter displays are a perfect fit for web manufacturing due to the simple, yet elegant, structure of two flexible substrates, a ChLC/polymer dispersion and light absorbing backpaint. Roll-to-roll processes allow for low cost manufacturing and high volumes due to reduced substrate and materials handling and the continuous web transport of displays at a rapid rate. Web processing displays takes advantage of the inherent display flexibility during the building process, unlike the batch rigid based processes that try to attach the flexible substrates to rigid carriers.

2. EWRITER DISPLAYS

2.1 Fundamental Science

ChLC material is a natural reflector as the inherent chiral structure of ChLC leads to a Bragg-type reflection of the incident light.³ Reflective ChLCDs have selective reflection properties. For normal incidence, the reflection of light occurs within a certain bandwidth $\Delta\lambda = (n_{\parallel} - n_{\perp})p$, where n_{\parallel}, n_{\perp} are the components of refractive index locally parallel and perpendicular to the liquid crystal director, p is the cholesteric pitch. An example of typical reflection spectra for the Boogie Board display is shown in Figure 2 (Left). The pitch is defined through the concentration c of a chiral dopant and *helical twisting power* (HTP) of the chiral dopant as follows: $p = \frac{1}{c \cdot \text{HTP}}$. ChLCDs are bistable and can be switched between two stable states:

planar, the reflective state, and focal conic, the slightly scattering transmissive state. Being bistable, ChLCDs require power only when being switched from one image to another. The eWriter display uses written pressure to write lines to the planar texture and a small voltage pulse to switch or erase to the focal conic texture. A schematic showing the transitions between the different textures of the eWriter display is shown in Figure 2 (Right), where the planar texture is created by pressure or flow of the ChLC and the focal conic texture is created by applying a small voltage pulse to the display.

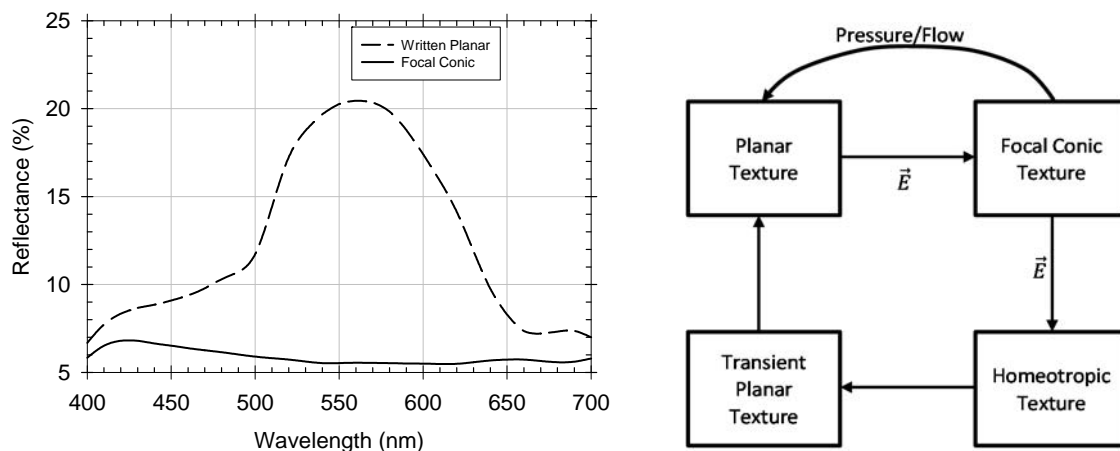


Fig. 2. (Left) Reflection spectra for a typical Boogie Board eWriter display. The written planar texture has a peak bandwidth in the yellow green, approximately 570nm. The focal conic texture appears as the color of the backpaint, in this case the backpaint is black. (Right) A schematic showing the texture transitions for the Boogie Board eWriter display.

When the written image is erased, the written planar image is electrically switched to the focal conic texture and during the high voltage pulse the cholesteric helix is untwisted to the metastable homeotropic texture that relaxes to a metastable transient planar texture and then to a stable planar texture. During the following low voltage pulse, the switched planar texture is electrically switched to the focal conic texture.⁴



The Boogie Board eWriter display consists of two flexible substrates each with PEDOT/PSS (poly (3,4) ethylenedioxythiophene/polystyrenesulfonic acid) as a conductor, also referred to as conducting polymer (CP), a cured dispersion of ChLC and polymer between the substrates, and spacers to maintain the cell gap. A cross section of a typical Boogie Board eWriter display is shown in Figure 3. The back of the Boogie Board eWriter display is typically flood coated with an absorbing ink but as we have shown in previous publications, patterned ink images can be coated on various display layers.⁵ In addition, the ink colors can vary as is shown in publication.⁵ The conductors for this display are unpatterned and the display can be simply cut into the desired shape for the final product. The eWriter electro-optic layer contains ChLC materials and polymer structure to create good line acuity.⁶ The photopolymerizable ChLC dispersion results in polymer pillars surrounded by ChLC, allowing the ChLC to flow as localized pressure is applied. Figure 4 shows SEM micrographs of the polymer pillar structure confirming that the ChLC is not encapsulated by the polymer but is allowed to flow around the polymer making the display rewritable without destruction. The pressure induces flow in the ChLC resulting in a written bright line on a dark background. Polymerized dispersion of liquid crystal and polymer have good flexibility and many possible uses.⁷

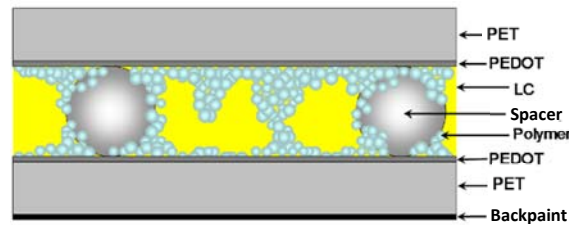


Fig. 3. Cross-section view of the Boogie Board eWriter display. The polymer forms pillars that support the substrates but do not encapsulate the ChLC.

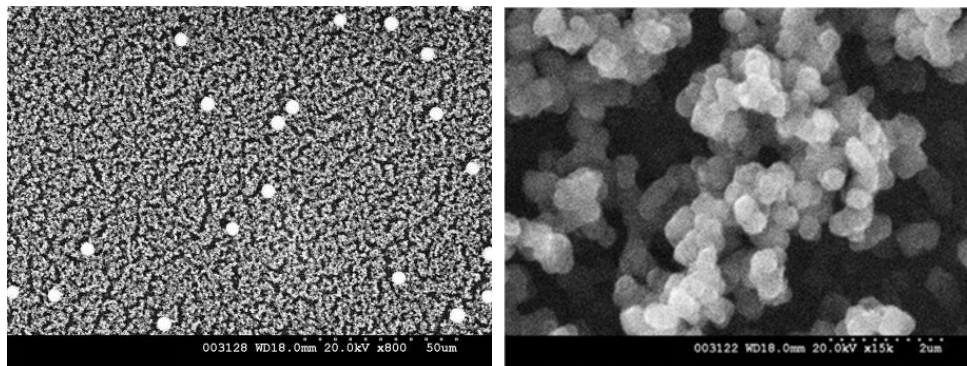


Fig. 4. SEM micrographs of the polymer structure formed within the Boogie Board eWriter display. The spacers show up as solid white circles in the low magnification image on the left. In the higher magnification image on the right a channel structure for the liquid crystal is evident (the black regions).

The Boogie Board eWriter display has a focal conic state that appears dark until the user presses on the top substrate with a point stylus or finger causing the ChLC to flow to the bright planar texture, creating a bright line on a dark background. To erase the image a small voltage is applied to the display, as shown in Figure 5, creating a uniformly black blank page to write on. The initial pulse applied to the display is V_P , 3.3Hz with a 50ms pause switches the display to the planar texture (V_P can be anywhere from 20V to 36V depending on the product). The following two pulses are V_{FC} , 3.3Hz with a 50ms pause fully erases the display to a focal conic texture (V_{FC} can have an amplitude of 9.5V to 18V). This waveform was chosen to switch the display because it fully erases the display for the entire operating range of the product, +10°C to +40°C. Shorter pulses are possible to fully erase the display, however, those require a different waveform for different temperatures. Both the basic eWriter architecture, including an LCD and electronics, and the advanced architecture, including an LCD, electronics, and digitizer, are available for OEM integration. KDI can provide electronics as part of the part for sale or specifications for an OEM company to design their own electronics.

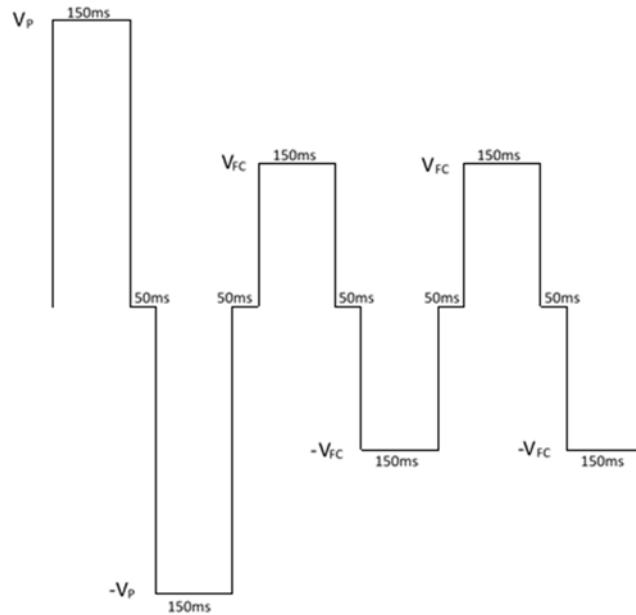


Fig. 5. Boogie Board switching waveform to focal conic texture. Initial pulse at V_p , 3.3Hz with a 50ms pause switches the display to the planar texture (V_p can be anywhere from 20V to 36V depending on the product). The following two pulses at V_{fc} , 3.3Hz with a 50ms pause fully erases the display to a focal conic texture (V_{fc} can have an amplitude of 9.5V to 18V).

The Boogie Board eWriter display is very touch sensitive and different line widths can be created on the display by the user varying their writing pressure and speed. The thickness and reflectivity of the written line increases with pressure. In addition, the Boogie Board eWriter display linewidth and pressure sensitivity can be tuned by varying materials. For instance, in the Boogie Board product family there are variations in linewidth depending on the market need for the particular device. It is possible to vary the linewidth of the Boogie Board products through proprietary processes and materials, as shown in Figure 6.

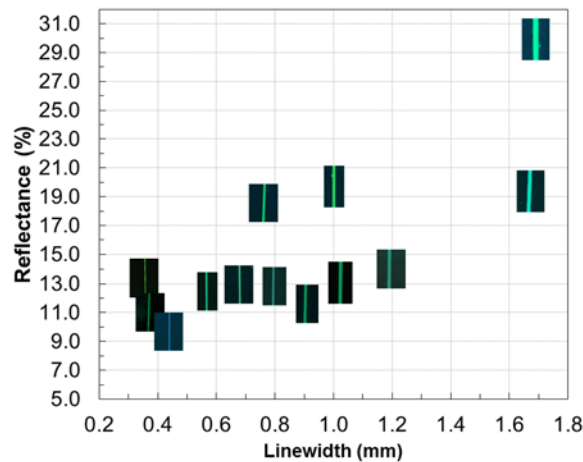


Fig. 6. Boogie Board eWriter display pressure sensitivity for different displays at the same pressure and speed. Notice that each data point shows the photograph of a line drawn on the Boogie Board eWriter display that has the line width shown for that data point. This measurement is made with a written line speed of 75mm/s and a 150gF applied to the stylus.

2.2 Products

There are several different eWriter displays in the Boogie Board product family, including devices for simply jotting down notes without a save feature and devices for electronically saving what has been written. The products that allow for jotting down notes are: Boogie Board original, Boogie Board Jot 8.5,



Boogie Board Jot 4.5, and the Boogie Board Play n' Trace. The Boogie Board Sync™ allows users to not only write images on the writing tablet but also allows the user to save what is written.

2.2.1 No Memory Products

The no memory products have the “pen on paper” writing feel that Boogie Boards are known for along with the instantaneous writing response. There are functional coatings on the top substrate, including a hard coat to ruggedize the products and an oliophobic coating to reduce the appearance of fingerprints. The no memory product family can be seen in Figure 7. The Jot 4.5 product has the thinnest line width at 0.9mm, with the next thickest line width for the Jot 8.5 product with a line width of 1.0mm, while the Play and Trace product has a line width of 1.3mm, and the thickest linewidth is on the Boogie Board original with a line width of 1.4mm (linewidths measured at 0.75mm/s written line speed and 150gF applied to the stylus). This meets the desire to have a thicker line width for a toy product such as the Play n' Trace and a thinner linewidth for a small handheld product such as the Jot 4.5 so more writing can fit into the smaller screen size. The Jot 8.5 product has an app that allows users to record images and will be discussed in more detail in a later section.



Fig. 7. Boogie Board products for jotting down notes without save feature. From left to right: Play n' Trace, Jot 8.5, Jot 4.5, and Original Boogie Board.

2.2.2 Toy Products

Recently, several new and exciting toy products have been developed using the Boogie Board eWriter displays. There is the Clearview™ product line that utilizes the concept of a semitransparent eWriter display, allowing the product to be used in both the reflective and the transparent mode. There is also the Scribble n' Play featuring Color Burst product that utilizes the concept of a multicolored eWriter display, which allows for the product to be used as a multicolor reveal writing device.

The Clearview product line includes the Play n' Trace product that was launched in late 2015 and is shown in Figure 8 on the left and the Jot 4.5 featuring Clearview eWriter display that will be launched spring 2016. The Play n' Trace is a larger product with a unique round shape, while the Jot 4.5 featuring Clearview is a 4.5" diagonal rectangular display similar in size to the standard Jot 4.5. The semitransparent display in both products has high contrast in both reflection and transmission mode, and has high clarity in transmission mode.⁸ This allows one to view objects behind the semitransparent Boogie Board, while in use. With these properties, the Clearview product line can be used as a stand-alone Boogie Board and also as an electronic tracing paper. The tracing function adds a fun aspect to the display and when coupled with handwriting, coloring or problem solving sheets behind the display adds learning to the mix. The exact color of the final display with semitransparent blue backpaint is a combination of the additive reflective colors of the ChLC layers and the subtractive reflective colors of the ink layer along with the color of whatever is behind the device. The optical properties of the Clearview eWriter displays can be seen in Figure 9. The Play n' Trace product has an associated app that allow users to play with the device in conjunction with a tablet or phone for new and exciting tracing and game opportunities. The Jot 4.5 featuring Clearview will have a similar app allowing the product to be used in conjunction with a tablet or phone.



Fig. 8. (Left) Play n' Trace product. (Right) Jot 4.5 featuring Clearview product. Both products feature the Clearview eWriter semitransparent display that allows for use in either the reflective mode or the transparent mode

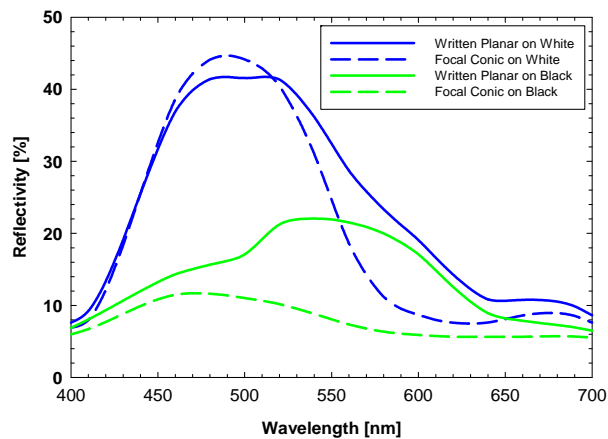


Fig. 9. The reflection spectra of the Play n' Trace eWriter, as measured on a white and black background.

The Scribble n' Play product, featuring a Color Burst eWriter display, introduces for the first time a multicolored eWriter display allowing users to write in different colors at different locations in the display, Figure 10. In the Color Burst eWriter display, the writing surface is the color of the absorbing background until written on, at which time the color of the writing will depend on the color reflected by the cholesteric liquid crystal layer and the absorbing background at that particular writing location.⁹ This toy is comparable to scratch art paper (removal of black wax coatings to reveal a hidden pattern), however, it is reusable and without the messy waxy residue¹⁰ or application of a wet reducing agent.¹¹ To further enhance the appeal of this eWriter as a fun and exciting toy, the reflectivity and the pressure sensitivity was greatly increased to allow pressure from a rubber stamp or roller to create images while maintaining palm rejection.

To create an eWriter display whose writing color changes with location requires changing the peak Bragg reflection wavelength of the cholesteric liquid crystal at various locations across the display. This is achieved by varying the amount of chiral dopant in the ChLC to change the reflected color and then depositing the different colors of ChLC in different locations on the eWriter display. This product is still made with the same low cost, environmentally friendly roll-to-roll volume manufacturing processes as all other Boogie Board eWriter displays but offers the exciting new experience of different colored writing. The Scribble n' Play product will have an associated app for recording images similar to the Jot 8.5 app, however, the Scribble n' Play app will allow users to save their images in the multiple colors seen on the Color Burst eWriter display.



Scribble
n'
Play™

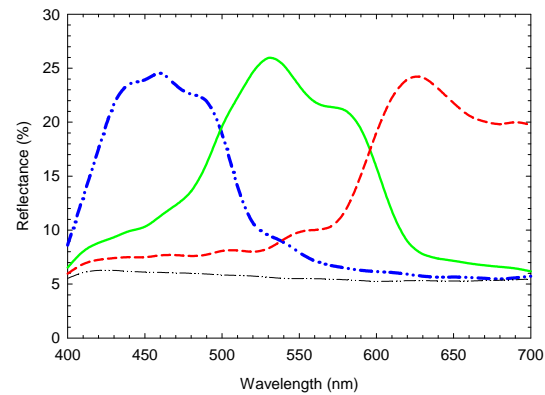


Fig. 10. (Left) Scribble n' Play featuring Color Burst product. (Right) The reflection spectra of the Scribble n Play eWriter.

2.2.3 Memory Products

The Boogie Board Sync device, shown in Figure 11, offers the same paper-like writing feel as other eWriter displays while adding the ability to electronically save written or drawn images. The saved images can be viewed or transferred via USB or wireless Bluetooth connection to a computer, phone, or other mobile device. Images are saved as vector PDF files which allows for resizing without any degradation of image quality. In addition, the Sync device has a real-time drawing mode that allows the user to create a virtual whiteboard when the Sync is connected to a computer with a projector. The device architecture includes a Boogie Board eWriter display, a high resolution Electro-Magnetic Resonance (EMR) digitizer located behind the display, and a passive inductive pen. When writing on the device, the pen pressure applied to the Boogie Board eWriter display creates the bright written image, while the electromagnetic interface between the pen and digitizer enables capture of the written image into internal device memory. Once the user has completed writing an image or has reached the end of the page they simply press the “Save” button and the image becomes available via Bluetooth or USB as a PDF file on the Sync device’s file system. The Sync device has a rechargeable battery which is charged through a standard USB connection. The linewidth of the Sync Boogie Board eWriter display is 0.8mm.

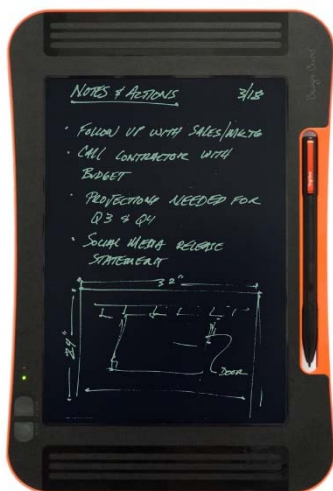


Fig. 11: Boogie Board Sync writing tablet device.



The Sync device is supported by a full suite of software and apps that have been developed for use with several different mobile environments and computer platforms and have been localized for different countries. The software and apps provide for automatic download of saved images from the Sync to a host device, storing and viewing of downloaded images, and sharing of images to cloud-based services such as Evernote, as shown in Figure 12. An option to convert the PDF images to PNG format increases the number of supported sharing services. Currently supported platforms include iOS, Android, Windows, and OSX. Examples of these apps in the real-time drawing mode are provided in Figure 13.



Fig. 12: Boogie Board Sync writing tablet ecosystem and use model.

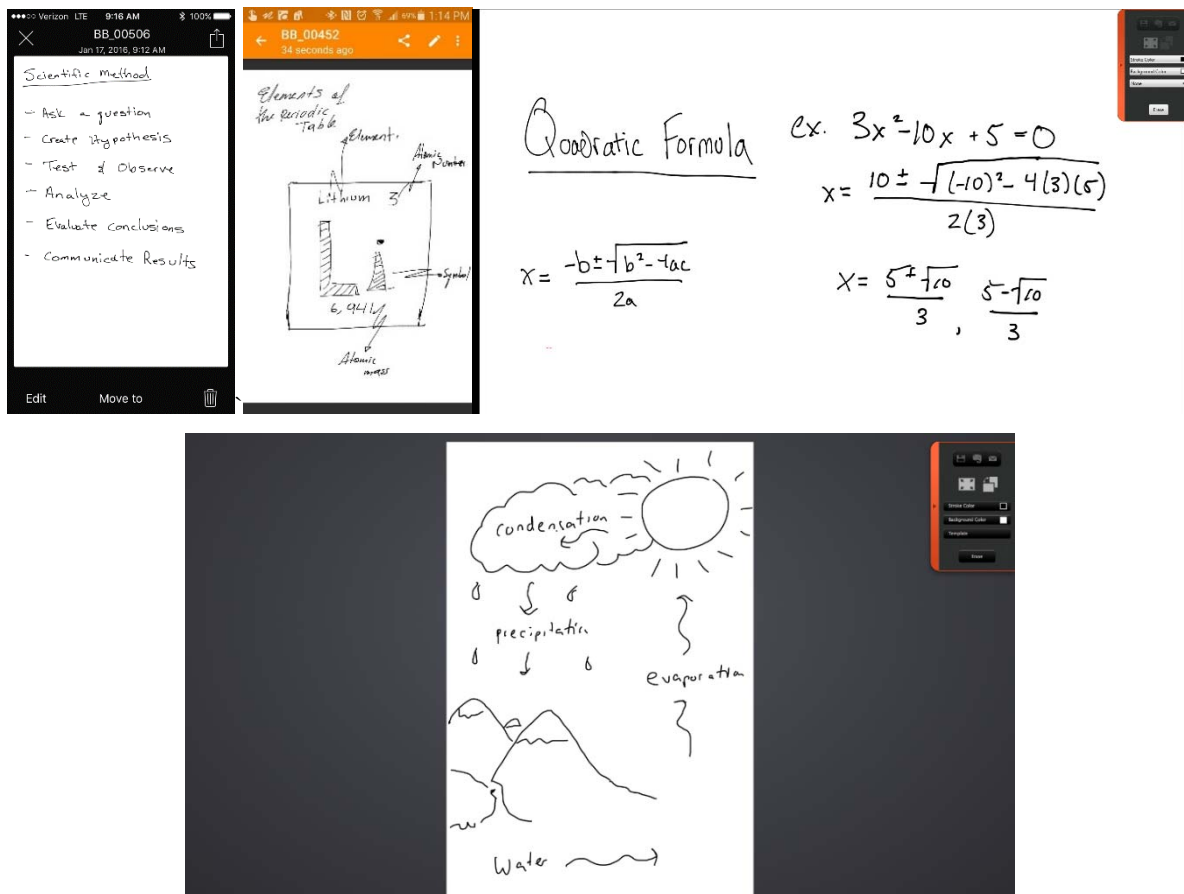


Fig. 13: Boogie Board Sync app real time drawing mode for IOS, Android, Windows, and OSX respectively.



In addition to the Sync device's internal saving capability, the Jot 8.5 has an external saving capability via an associated app. The app (used with IOS and Android) works by taking a photo of the Jot 8.5, once it has written information, and then inverting the image so the writing appears as black lines and the background appears white, Figure 14. In addition, the Scribble n' Play featuring Color Burst product will have a similar app that allows users to record their written images, however, the Scribble n' Play app will allow users to save their images in the multiple colors seen on the Color Burst eWriter display.



Fig. 14: Boogie Board Jot 8.5 app allows note saving. Jot app takes a photo of device and inverts image to black writing on a white background.

2.2.4 OEM Products

Boogie Board eWriter displays are also a natural fit for integration in other products such as: consumer electronics, furniture, apparel and accessories, appliances, vehicle dashboards and visors, among others. The Boogie Board eWriter displays are an ideal writing companion for numerous devices, allowing the consumer to use the existing product along with a rewritable and environmentally friendly note taking device. Indeed, the Boogie Board eWriter display has already been introduced in the first ever mobile phone portfolio cover through the Tegware Bagel, which is an iPhone case with jot board and has now come out with updated versions for iPhone 6, see Figure 15. The Boogie Board eWriter display can be built in custom shapes and sizes even including, holes inside the display, organic shapes, curves, and inside corners. There are many display sizes available from 2.5" diagonal to large area. Not only can the Boogie Board eWriter display be cut into organic shapes but it can also be conformed to fixed curvatures. Both the basic eWriter architecture, including an LCD and electronics, and the advanced architecture, including an LCD, electronics, and digitizer, are available for OEM integration. KDI can provide electronics as part of the part for sale or specifications for an OEM company to design their own electronics.



Fig. 15: Tegware Bagel iPhone portfolio cover case with Boogie Board eWriter display.

2.3 Reliability

2.3.1 Environmental Tests

Boogie Boards and Boogie Board eWriter displays have passed extensive environmental testing. As part of the standard product development cycle, all Boogie Board products first have an appropriate environmental testing document developed that defines all tests the parts must pass along with the passing criteria. The roll-to-roll manufactured parts are exposed to a battery of tests. Typical tests include;

- 65°C/85%RH for 500 hrs
- 65 °C for 100hrs
- -30 °C for 72hrs
- Thermal cycling 155hrs
- Shock and Vibration
- Consumer Safety Rating/Toxicity
- Battery Testing, ESD testing
- FCC Testing
- Suntesting (Q-Sun chamber for 72 hours at 0.68 W/m² irradiance (measured at 340nm) at 50°C

2.3.2 Writing Tests

Boogie Boards and Boogie Board eWriter displays are exposed to repeating writing tests with a Fisnar F4400N Cartesian robot. There are various different writing patterns, written linespeeds, and masses applied to the stylus during these writing tests. We have developed writing tests specifically for the Boogie board that are designed to mimic real life usage for a note taking device, since existing writing tests used for touch screens do not apply to this display mode and application as the display is not written on with the same frequency and repeated location as supermarket signature pads, tablets, or other touchscreen applications. To control the writing and reproducibility, a Fisnar F4400N series xyz robot is used to write on the devices. The actual writing is completed with a stylus that is attached to the robot arm. The stylus



holder is designed so that the mass on the stylus can be increased or decreased, with minimal friction by including a bearing lined barrel.

The repeating pattern presented here is a cursive writing pattern where the image is erased between each write. The results of the cursive writing test on the various Boogie Boards with increased mass are shown in Figure 16 below. Note that the points under the arrow are not wear points but simply the completion of the test. All three Boogie Boards exceeded 100,000 writes with 150 gram-force applied with no visible wear as shown in Figure 16. Reliability and durability of Boogie Boards is discussed in much more detail in two publications.^{12,13}

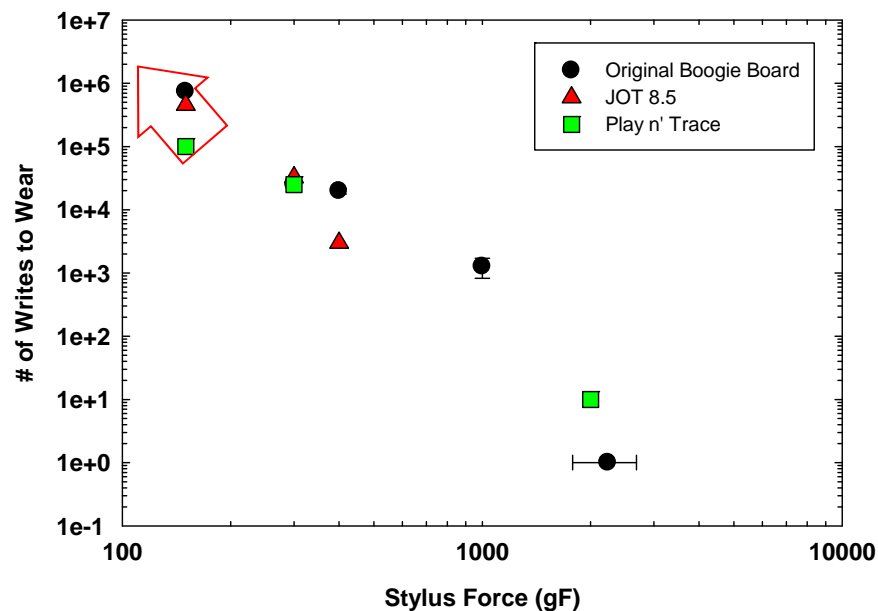


Fig. 16: The results of the cursive writing test pattern written on the Original Boogie Board, JOT 8.5, and SYNC Play n' Trace. The graph shows the change in the wear point when the mass is increased. Note that the points inside the arrow are not wear points but simply the completion of the test. All three Boogie Boards made it to >100,000 writes at 150 gram-force applied with no wear.

3. ROLL-TO-ROLL PROCESSING

Kent Displays has two high volume roll-to-roll manufacturing lines. Both lines unwind rolls of plastic film coated with a transparent conductor, such as indium tin oxide (ITO) or CP, and perform the necessary process steps to effectively convert the roll of film into finished displays. Both lines have various stages of cleanroom based on the sensitivity of the area to particulate.

Neither production line produces waste water or chemicals requiring treatment but rather utilizes a closed loop system for process cooling. Environmentally friendly UV curable materials and processes are used throughout the manufacturing process. UV curing lowers air pollution, as well as the energy required to treat exhausts by dramatically reducing solvent vapor production compared to more conventional thermal curing processes.¹⁴ An example of one of the roll-to-roll manufacturing lines is shown in Figure 17.



Fig.17. Photograph of one roll-to-roll production line. Production manufacturing occurs in a Class 10,000 clean room.

4. CONCLUSIONS

KDI has multiple years of experience in volume manufacturing of flexible displays, development of materials science and display technology, web process engineering, product development, and commercialization of consumer products demonstrated by the company. Indeed, the creation, by KDI, of an entirely new product category, electronic writing tablets, is a testament to the capabilities of the team at KDI. The company is committed to volume roll-to-roll manufacturing of the Boogie Board products in USA along with a clear path to commercialization.

Flexible displays represent a paradigm shift in the display world that result in a completely different form factor for the final product. As flexible displays become more pervasive, device designers will begin to identify new and different applications and form factors for even more applications creating a market niche for flexible, rugged displays. Kent Displays is a pioneer in this field and positioned perfectly to take advantage of this opportunity, as our roll-to-roll manufacturing processes have been developed and vetted through several years of production manufacturing of the Boogie Board. The roll-to-roll manufacturing processes are well designed to produce the Boogie Boards but can also be easily transition to other market applications as is needed. The roll-to-roll processes developed at Kent Displays are mature and require minimal resources to run the processing line, allowing these flexible displays to be built with significantly reduced operator costs.

The electronic writing tablet market is a novel way to take notes without cutting down trees and creating waste. This application has a very simple but elegant construction with millions of units sold to date over the previous 5+ years. The pressure induced, flexible, roll coated, writing tablet display, allows note taking with the user experience, writing feel, and writing speed similar to that of paper along with being sunlight readable. The product family offerings include not only scratch pad type devices with no memory and lower cost but also offer the Sync device which allows file saving of written notes. All of the Boogie Board devices have passed extensive environmental and writing tests to create a product with over a million switches possible and an expected 5 years of consumer life.



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