Liquid Crystal Displays:
Reminiscence of the Early Days

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I. Introduction

In many respects, the story of liquid crystal display technology has all the ingredients of a good novel. There was excitement, frustration, success, failure, and personal tragedy. I am not going to explore all aspects of the story, but rather concentrate on those aspects which I feel might be of interest to younger engineers, some of whom are destined to follow similar paths with different technologies in the future. I will focus on my personal reminiscences of the work at RCA Laboratories because that is where the full potential of nematic liquid crystal displays was first discovered and demonstrated. Other workers, for the most part, were working on thermal effects in cholesteric liquid crystal materials. Permit me to apologize ahead of time for omissions. Since the work on LCDs that I am going to discuss began approximately 40 years ago, I trust that you will forgive my age related moments of forgetfulness. For me, it all happened least, several lifetimes ago.

II. The Foundation

Every story has a beginning, and this one began with the search for a dissertation topic in 1961. I had finished my written and oral examinations for my doctorate at Princeton University under RCA Laboratories' sponsorship. In those days, young scientists and engineers were in great demand in America. RCA Laboratories recruited very competent engineering graduates and then financed their graduate education while enabling them to work part time and summers at the Laboratories on meaningful research projects. I had worked for over two years in the then emerging field of solid-state microwave devices with Dr. Kern Chang under the overall direction of Dr. Leon Nergaard. I was involved in the original work on solid state parametric amplification, solid state millimeter-wave generation, and the tunnel diode down converter. It seemed altogether logical that I would do my doctoral dissertation in the solid-state microwave field. As a matter of fact, it was too logical, and that bothered me a bit. The competition for new ideas in the field was becoming more difficult, and having had the experience of exciting research, I wasn't particularly interested in pursuing a problem simply to get my degree. Fortunately, Dr. Sol Harrison at the Labs was beginning some interesting work on organic semiconductors and I was fascinated by some of the things that he was trying to do. Sol was one of the most intellectually stimulating men I have ever known and a born teacher. I now had two choices – stay in solid-state microwave work where I had modest identity and achievement, or move on to the "dirty" world of the organic chemist, where I knew nothing.

It was at this point that I received some excellent advice from Dr. Leon Nergaard, the director of the microwave research laboratory at RCA that, in retrospect, may have changed my career. . Dr.Nergaard said, “Look, George, you may never have another opportunity to try something completely new like this again. Use this thesis time wisely. Do something different. Microwave solid-state electronics is fine, but organic semiconductivity is more wide-open.” I mulled these thoughts over in my mind and discussed them with Professor George Warfield at Princeton University. Professor Warfield felt strongly that dissertation topics should be discovered by the student – not assigned by a faculty member. He agreed that organic semiconductivity would offer the greatest learning experience and, so, as an electrical engineer, I left the relatively “safe”, for me at least, world of inorganic materials behind. I finished my thesis in one year, publishing five papers on the results, including several scientific firsts in the transport properties of molecular crystals. The transport properties of molecular crystals were interesting, but I simply was not going to make “organic transistors” that were at all competitive – now it was time to apply what I had learned to other challenges.

The laser had emerged on the scene at about this time and was commanding most of the attention at the Laboratory. I wanted to be part of this emerging field. There was a need for optical modulators and people were experimenting with the old Pockels effect standbys – KDP, ADP, ZnS and CuCl. KDP and ADP, due to their crystal symmetry, had only a longitudinal effect which made their half-wave properties voltage, not field, dependent and the voltages were in the kilovolt range. Zinc sulfide (ZnS) and cuprous chloride (CuCl), with cubic crystal structure and lacking a center of inversion, had a transverse electro-optic effect. Nevertheless, it was difficult to grow single crystals of these materials in their cubic form. No one seemed to know how to go about structuring a materials effort to tailor an improved Pockels effect modulator material. Molecular modifications were relatively easy to perform with organic materials and no one else seemed to be interested in these, so I decided to have a look at the problem. I selected hexamethylene tetramine (HMTA) from the *Handbook of Chemistry and Physics* because it was cubic and lacked a center of inversion, and Dr. Joel Goldmacher, an organic chemist from Purdue University who had joined the organic semiconductor work, grew the crystals. The material did have an interestingly large Pockels effect, but the material was relatively soft, water soluble, and attempts to substitute groups on the basic HMTA molecule resulted in compounds with monoclinic rather than cubic crystal structures.

At the same time, I noted that electro optic effects, the change in the index of refraction as a function of applied electric fields, could be related back to the molecular Stark effect via the classical Sellmeier equation for refractive index. There appeared to be very fundamental reasons why the Pockels effect was small for most materials – the molecular Stark effect is a small effect even at fields of 10^6 V/cm because the externally applied fields were always several orders of magnitude less than the internal crystal field.

I began to ponder ways in which I could control the local fields of materials by means of an applied electric field and was attracted to some experiments on the orientation of nematic liquid crystals in external electric fields by Dr. Richard Williams of RCA (in my opinion, one of the finest physical chemists in the country). Liquid crystal research was not new. Liquid crystals were discovered in 1888 by Reinetzer and the early research peaked around 1900. This was followed by a period of quiescence which lasted for a full generation of scientists. There was a renewal of interest in the late 1920’s and early 1930’s followed by another period of inactivity which lasted about 30 years. Now the field was stirring once again with work on cholesteric liquid crystals leading the way. After reviewing William’s work, I reasoned, perhaps naively, that the local fields in the nematic liquid crystal were determined by the molecular order which, in turn, was a function of the applied field. A strong dye was selected and used to dope the nematic liquid crystal butoxy benzoric acid. The mixture was sandwiched between two glass slides coated with transparent tin oxide electrodes and placed under a microscope with a hot stage. Heating was required because there was no known material at the time which had a nematic liquid crystal phase at room temperature. A dc voltage of several volts was applied and we watched the cell change color from red to colorless as a function of the applied field. It was found almost immediately that the effect was more dramatic with a polarizer in place. The device was drawing less than a microwatt of power per square centimeter and we were switching color with voltages of less than ten volts in some cases! It was the Fall of 1964. The wall-sized flat panel color TV was "obviously" just around the corner if you believed that "obviously" meant another two decades. As we all know, excitement can certainly cloud one's objectivity.

All we had to do was wait for the integrated circuit industry to go through repeated Moore's law cycles to produce the integrated circuits of the necessary complexity to perform the addressing function for LCD TV displays. This took at least another two decades. After several days of making more cells and demonstrating the effect to just about everyone at RCA Laboratories, we got back to more serious work. Our original search for a large Stark effect in a "guest dye" produced by external control of the local field via orientation effects in the host nematic liquid crystals was masked by the reorientation of the "guest dye" molecule along with the nematic liquid crystal host. Since the dyes were pleochroic (their optical absorption spectrum was a function of their orientation relative to the polarization of the incident light), we were observing the change in the absorption spectrum as we electrically switched the orientation. No one seemed to care that our original theory was not operative. What counted was that we had discovered a dramatic new effect.

About this time, Professor Peter Debye visited RCA Laboratories. I asked to see him. Because the project was company confidential, couldn't tell him about our successful experiments or show him the effects, but I did discuss my ideas with him in a general way. His speculation was that it could not be made to work. Dr. Vladimir Zworykin, the father of television to many, and an honorary Vice President of RCA, summoned me to his office to find out why everyone was so excited. I explained to him how I had stumbled on the guest-host color switching effect. I'll never forget his reflective reply: "Stumbled perhaps, but to stumble, one must be moving." We were moving. It was only the beginning.

III. Dynamic Scattering and Other Effects

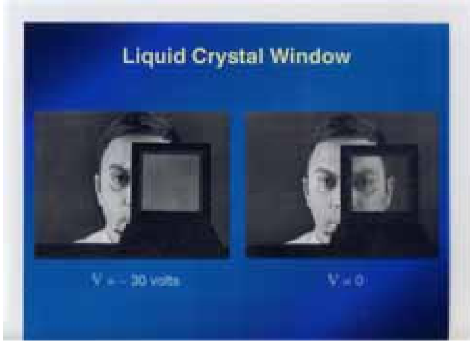
There were obvious problems with the guest-host effect. The dyes and their liquid crystal hosts were not stable over long periods of time in applied fields, and the effect was sensitive to surface orientation effects. It required polarized light, it was viewed in transmission, it required heating to maintain the host in its nematic phase, uniformity was a problem, and so on. We tackled these problems on all fronts. We found that the nematic liquids themselves had interesting optical switching effects when properly oriented on the surface of the electrodes and viewed in connection with a polarizer or polarizer-analyzer combination. But there was another more interesting affect that we observed in certain classes of nematic liquid crystals-those with negative dielectric anisotropy. Instead of orienting in the applied field, these materials exhibited a marked turbulence that turned them from transparent to milk white. The milk-white appearance required no polarizer to observe – it was purely a light scattering effect. We had discovered how to electronically control the reflection of light in a most striking and dramatic way. We had to think of a name for this effect and the term "dynamic scattering" was coined. The year was 1964 - a very exciting year indeed.

In the process of trying to increase the reflection efficiency, we doped the nematic liquid crystals with cholesteric liquid crystal materials. This led to the discovery of still another new electro optic effect. A dc electric field caused the material to become milk white and it remained in this state after the removal of the field. The transparent state was restored by an ac electric field. We had added a storage effect to the other discoveries. Those interested in the liquid crystal research at Kent State University under Dr. Glen Brown, at Westinghouse Research Laboratories under James Ferguson, and at other places were generating attention with their work on the impact of temperature change on the color of cholesteric liquid crystals. They were exploring their use as sensitive, easy to apply, temperature sensing devices in which the color of the cholesteric liquid crystal materials changed as a function of temperature. Our work on electric field effects in nematic liquid crystals and the dramatic display effects which we had observed were still closely held as company confidential information. We presented a few papers on the behavior of domains in nematic liquid crystals at the 1965 International Liquid Crystal Conference at Kent State University but were not permitted to divulge the most exciting aspects of our work – the discovery of several new electro-optic effects in nematic liquid crystals and the prototype flat panel displays we had built based on them.

It was clear that for dynamic scattering to have a major impact, we were going to need room temperature nematic materials. Joel Goldmacher, Joe Castellano, and Luke Barton went to work on the problem and in a relatively short period of time developed a mixture of Schiff base materials that was nematic at room temperature – another first. With these materials in hand, we began designing and fabricating prototype displays based on dynamic scattering. Lou Zanoni made important contributions in this area. Alpha numeric displays (reference Picture 1.), windows (reference Picture 2.) with electronically controlled transparency, static pictorial displays (reference Picture 3.), an all electronic clock with a liquid crystal readout (forerunner of the liquid crystal watch (reference Picture 4.)), and liquid crystal cockpit displays (including a cockpit mock-up (reference Picture 5.)), were fabricated. These prototypes got everyone excited and RCA Corporate management prepared to announce the discovery to the world with a press conference in June of 1968. The press conference drew national and international attention to the new effects and the potential of liquid crystal displays. The popular press was captivated by these materials that had the properties of liquids, and solids at the same time and literally hundreds of requests for information poured in overnight. We had reached the end of the beginning. Liquid crystal displays had been born.

Picture 1.

Picture 2.



Picture 3.

Picture 4.

Picture 5.

IV. Aftermath – Some Lessons Learned

Looking back, one of the key ingredients which made it all work was the ability of organic chemists and an electrical engineer to work together in an atmosphere of mutual respect. We simply weren't afraid to appear stupid to each other when working outside of our respective fields. This was the first lesson learned – the positive power of interdisciplinary research performed without the negative effects of excessive personal egos.

Liquid crystals, however, were viewed more as a threat than an opportunity by some with other commercial interests. They said, "it wasn't silicon," the materials were "dirty" by semiconductor standards and it was "too easy for the garage operators" to get into the business. The liquid crystal digital watch idea was not aggressively pursued because management thought there was "no market" and the problems of filling and sealing a liquid crystal cell which consisted of two pieces of glass (one with an evaporated aluminum film on the surface and the other with a transparent conducting tin or indium oxide film on the surface) were alleged to be "insurmountable." Our research group which had nursed the "baby" from conception to prototype displays turned to manufacturing technology and evolved processes which we felt could handle initial production. They were not adopted, but they did work. This was the second lesson learned – the negative power of the vested interests.

In retrospect, perhaps our team, suitably augmented, should have been given the responsibility for developing the business opportunity as well as the technology. We were the entrepreneurs; the ones who saw opportunities, not problems; the ones who had no vested interest. Perhaps that is the lesson to be learned about bringing new ideas to market. History seems to indicate that breakthroughs are usually the result of a small group of capable people fending off the criticisms a larger group of equally capable people with different interests that were not entirely technical. If one subscribes to this theory, it is not surprising that the Polaroid process was not nurtured by the largest photographic company in the world; that most vacuum tube companies did not succeed in the transistor business, and office copiers were not pioneered by the giants in the office equipment business. This was the third lesson learned – the negative aspects of technology transfer.

Today, when I hear people talking about the difficulties of "technology transfer," I immediately think that if the work was done in the right way, they wouldn't be experiencing these difficulties. As I see it, it is much better to form an interdisciplinary team of researchers, and product and manufacturing engineers. The researchers should remain in the majority and leadership role until key milestones, demonstrations and early prototypes have been achieved. It is then time to switch roles with the product and manufacturing engineers in the majority and in the leadership role supported by the researchers. During this phase, marketing support is needed to play the role of the customer's advocate.

I left RCA and the field of LCDs out of frustration in 1970. Later, others in the group left for the same reason – frustration. For me, the excitement and passion was gone. I went on to four other "careers" in the next four decades and never looked back. This was my fourth lesson learned – when the excitement and passion leave your work, leave with it. Go on to something else and remember what Wayne Gretzky, perhaps the finest ice hockey player of all time, once said, "Statistically, 100% of the shots you don't take, don't go in." He also said "I don't skate to where the puck is, I skate to where it is going to be." In my view, his wise insights apply to many professions and many aspects of life.

So, that's the way it was, as I saw it. A great bunch of young guys having fun working together and playing together. For Hemingway, Paris in the Twenties was a "moveable feast." Decades later, in a different place, and a different context, we experienced the same emotion.

**Portions of this presentation are based on my 1976 paper entitled, "Liquid Crystal Displays: An Experiment in Interdisciplinary Research that Worked" that was published in the anniversary issue of the IEEE Transactions on Electron Devices, Vol. ED-23, NO. 7, July 1976.