**Sue Nelson**

Hello, I'm Sue Nelson and thanks for joining me on Create the Future, a podcast brought to you by the Queen Elizabeth Prize for Engineering.

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It began in 2013 when the first QEPrize was awarded to the pioneers of the Internet. Two years later, the QEPrize went to those involved in controlled drug delivery, then in 2017 it was for digital imaging sensors, and in 2019 for the creators of GPS. And the fifth ever QEPrize has just been announced for the development of LEDs, with five engineers from Japan and the United States sharing the 2021 award.

**George Craford**

A few years ago, when the prize started, I have thought "Boy, that is a wonderful thing that is done to have a prestigious international prize like that for engineering" and to actually win it is the best career award I could have.

**Sue Nelson**

George Craford. We'll be hearing more from him and three other prize-winners during the podcast. Let's start with the winning innovation, LEDs are everywhere, used as bright torches on smartphones or in light bulbs in homes and offices. Invented almost fifty years ago, the first LEDs were low illumination, expensive and only came in one colour - red. Today's LEDs are low cost, highly efficient forms of bright illumination that can be found everywhere from computer screens and handheld laser pointers to traffic lights and concert light shows. And how apt that LEDs have even illuminated Buckingham Palace. LED stands for 'light emitting diode' and it's a device in the form of a semiconductor, like aluminium gallium arsenide, for example, that emits visible light when an electrical current flows through it. This device often has impurities added, in a process called doping, to make it more conductive and the materials produce particles of light, or photons, with specific frequencies and this determines the colour. The first LEDs used gallium arsenide phosphide, for instance, and this is why the light was red. It took decades of innovation before white LEDs could be produced. Now, like all the innovations that have won the Queen Elizabeth Prize for Engineering, LEDs have benefited society. It's their efficiency that's key because LEDs produce far less heat than conventional light bulbs, leading to more energy savings. This is why LEDs are often called lighting's 'green revolution', because they can play a crucial role in reducing carbon dioxide emissions. This revolution truly got underway with Professor Nick Holonyak. He studied electrical engineering at the University of Illinois in the United States and spent a year at Bell Telephone Laboratories. After military service, Holonyak then spent six years working for General Electric, the company founded by Thomas Edison. And it was there, in 1962, that Holonyak invented the first visible, in this case red, light emitting diode. Today he's the university's John Bardeen Endowed Chair Professor of Electrical and Computer Engineering and Physics. A perfect title because John Bardeen invented the transistor and Holonyak was his first student.

**Nick Holonyak**

It turns out I was very lucky because I had started working here at Illinois on semiconductors because of the business of the transistor. John Bardeen came here from Bell Labs in 1951. I already had a master's degree and knew how to do electronics with vacuum tubes. Here, I had an opportunity to learn what the transistor was all about. So, I had started in 1951 and by 1954 I had done a PhD thesis. By 1954 I found myself at Bell Labs working on silicon devices. And in fact, my boss at Bell Labs, John Moll, was one of the greats. And I was very lucky to be working with him. And we did some of the first silicon diffused junction devices with an oxide layer. And all of that wound up in California and was the basis for the name 'Silicon Valley'. And so, I know, or I knew then, because most of those people are dead, Bardeen is dead, the people he worked with and some of the people that I worked with, almost all of them, because I'm 92 and most of them were older than I. And so, a lot of the people that I started with go right back to the very beginning. The transistor was only a year or two old when I was already working in that area.

**Sue Nelson**
I know you're called The Godfather of LEDs. It does sound like an era of amazing discovery.

**Nick Holonyak**
But many other devices too!

**Sue Nelson**
Yeah, what a time! So, you were working with John Bardeen and you were improving and developing semiconductors. And you were the first to make silicon tunnel diodes?

**Nick Holonyak**
That's right. In fact, I maintain that after Abraham Lincoln, in Illinois, and in America, one of the greatest men is John Bardeen. And there's an interesting story about how he and I got along because he became from a well-off family. I came from a very poor family. But somehow or other, I was like a younger brother to him. And he tracked me for about nine years when I was about in the world and industry and asked me to come back to the university and bring III-V semiconductor work back to Illinois. And what I was working on was light emitters, lasers, and so forth. And so, the only real laser that existed that you could see at the time I returned to the University of Illinois was the ruby laser that Ted Maiman made. He went up Bell Labs because Bell Labs had written off the Ruby laser. And I wanted to make a laser that was driven not by a big intense photographic lamp, but was driven by current directly, and I thought a semiconductor would do it. And it did, I made my own crystal and gallium arsenide phosphide and made the first red visible spectrum alloy laser and that got, for me and my wife, a trip to Japan in 1995 to get the Japan Prize.

**Sue Nelson**
This work that you did, it has changed the world we live in. Do you ever reflect on that?

**Nick Holonyak**
Well think of it, you're in science news reporting and when you think back, a photographer was always carrying a big load of equipment and all that. Now, that's all replaced with integrated circuitry, semiconductor materials, and now lamps, flash lamps and everything else. I was able to work out a simple proof that, maybe someone will think of a different way to generate light.

**Sue Nelson**
So how do you feel about being awarded the Queen Elizabeth Prize for Engineering?

**Nick Holonyak**
Well, I think it's a great thing and I want to thank all of you because this is a great honour and I really appreciate that. I'm just sorry that the some of the old timers are not alive because they would appreciate this.

**Sue Nelson**
The rather wonderful Nick Holoynak. What a career he's had starting out as a student under the inventor of the transistor. Now, for 10 years LEDs could only be produced in just that one colour, red, until our next winner managed to produce a brighter red LED and the first yellow LED. And it was by one of Nick Holoynak's former graduate students. Until he retired, Professor George Craford was the chief technology officer of Lumileds

Lighting, which made the LEDs that lit up Buckingham Palace in 2006. Craford studied physics at the University of Illinois before joining the Monsanto Chemical Company to lead its LED technology group. After inventing the yellow LED there in 1972, he joined Hewlett Packard in 1979 where his team pioneered aluminium gallium phosphide LEDs using a process called MOCVD: metal organic chemical vapour deposition.

**George Craford**
The colour of an LED is determined by the semiconductor material that you use for it. And Nick was the one who pioneered using semiconductor alloys. His alloy was between gallium arsenide and gallium phosphide to make gallium arsenide phosphide. And what we did at Monsanto was add nitrogen doping, which is an impurity that we put in the semiconductor to make it, in the case of these materials, that makes it more efficient at shorter wavelengths. Instead of being limited to red and if you try and make the red go to yellow by just adding more phosphorus to it, the efficiency drops rapidly, because of adding this isoelectronic impurity, which had been recently predicted, theoretically, enabled us to go to higher percentages of phosphorus and maintain high efficiency. And so, we were able to go to yellow. The colour is determined by the energy gap of the semiconductor and by adding more phosphorus, the energy gap increases. But the efficiency without the nitrogen would decrease sharply and not allow light emission of any significance in the yellow, but by adding the nitrogen doping, we were able to achieve high-performance yellow, as well as red, and red / orange and other colours.

**Sue Nelson**
And this was the first time you've got this very high brightness as well, of light, this yellow and the amber?

**George Craford**
Yes, it improved the brightness quite a bit. And over time, and over just a few years, we were able to improve the performance of LEDs by about 10 times by using this isoelectronic nitrogen.

**Sue Nelson**
And part of the success as well was you and your team pioneering LEDs that were using this MOCVD, this metal organic chemical vapor deposition, because it allowed you to commercially develop it.

**George Craford**
When I went from Monsanto to Hewlett Packard, we started working on the Al-In-Ga-P aluminium, indium, gallium, phosphide materials for LEDs. And that was quite a journey. But we were able to ultimately achieve about a 100-fold improvement over the earlier technology that I was talking about. And so, this got us into the very high brightness red, orange and yellow region. And to do that technology development takes, there's a lot of steps that you go through trying to figure out, well, one thing I would say about LEDs, they have light output inside. You can get efficiency inside the junction, but you have to get the light out of the LED to do any good. If you just have a cube of semiconductor material with light generated at the junction between the p and n-type regions, it tends to rattle around inside this chip, we sometimes say it's like a graveyard for photons in their little tombstone, because the LED photons that you have generated, many of them get absorbed in the chip. And so, part of it is to develop ways to extract the light from the chip. We improved that by semiconductor bonding a thick piece of gallium phosphide on the bottom that were transparent so we could extract the light from the devices. So, it was both a matter of developing the efficient generation of light inside the chip, which was quite difficult. And the structures that you use to do that involve quantum wells and many layers, today's LEDs have, many of them have 100 layers in there, some of the layers just a few nanometres thick. And so, these are complicated structures, and there's an unlimited number of combinations you can do to generate the light inside the chip. So, you have to combine all these features in order to get good light output. And then of course to get to a production device that you can sell on the market, you have to be able to produce these in

high volume. And they can't degrade. And that's one of the difficult things about any LED technology is combining those features, you go in the lab and after a lot of work, you make something that is highly efficient. Then you're all excited, and then you put it on a reliability test, and it fails in a few days and that doesn't work at all, in fact the test usually takes longer. So, it's difficult because you don't get feedback as to whether your structure is going to be satisfactory or not until you get the reliability data back. And often, there is a trade-off between efficiency and the reliability that you need to have in order to make a commercial product. And then that still doesn't count for the issue of uniformity and yield, which in industry, of course, is an important thing. Basically, every wafer has to be the same and so learning how to control the uniformity, and to get the highest possible efficiency, and to have the device so it is reliable and can last for 10s of 1000s of hours is a tough combination.

**Sue Nelson**
Would you say that persistence is one of the qualities that an engineer requires? And patience?

**George Craford**
I would definitely say that persistence is required. I suppose you can get lucky. But yeah, for most engineering work I think it's exciting, it's interesting, but it's challenging and you have to keep working at it.

**Sue Nelson**
For Craford it's been a 50-year journey of constantly improving on the technology. Decades later at Lumileds he went on to develop the first high power white LEDs. But there were several essential stages that were required before that could happen. And the role played by the third winner, Russell Dupuis, allowed for one them, the commercial development of high-quality semiconductors. Dupuis is a professor at Georgia Institute of Technology and like Nick Holoynak, is also a University of Illinois graduate in electrical engineering. He was working at Rockwell International when became the first to develop that MOCVD process, metal organic chemical vapour deposition. It could be applied to high quality semi-conductors and devices to produce high performance LEDs. Here's Dupuis explaining that MOCVD process in more detail.

**Russell Dupuis**
Well, the last three letters chemical vapor deposition, are generally used to describe processes that use, as the word says, chemicals in a vapor phase form. So, a gas form to deposit a material to create a solid film, in this case, the metal organic part, the MO part comes from the fact that these compounds, when they were developed many years ago in the 1920s and 1930s, were called metal organics because they had metal atoms that were bonded to organic molecules like methyl radicals or ethyl radicals. So relatively simple organic radicals. And the value to this was that metals could be transported into chemical reactions in a vapor phase in the process. So, the innovation of the MOCVD, which was invented by a chemist named Harold Manasevit in 1968, is that you can transport metals with relative ease to a gas environment where you can mix that vapor with other compounds in the vapor phase and then thermally decompose them to form a solid film composed of the metal, plus the additional elements you might add in gas form. So, at the time the MOCVD process in the early 70s was not used widely because it was considered to be fairly impure and produce lower quality material. It turned out that was simply due to the fact that the chemicals, the initial chemicals we used weren't very pure because no one had bothered to purify them because they weren't important. An interesting story, I think about this process, when Dr Manasevit was first working on this, he called a large US chemical company that was making some of these compounds commercially for industrial use and he asked them for some of this material, and they said, "Oh, that's very nice. How many railroad tank cars do you want?". Literally, they were making this by the ton, but at very low purity. So, it took a long time for this small niche application of making semiconductors to be attractive enough for some chemists to go and purify these compounds. That really was an important event, but it became driven by the need to grow semiconductors. So once my work was published

in 1977 in this field, a lot of people were surprised and then changed their mind about it and started to work on it themselves. So many groups in the UK, in France, in Japan, got involved in this work, Germany as well. Eventually people started to develop this, and then the chemicals got purer, and our materials got better.

**Sue Nelson**
So, this is very important to produce these high-quality semiconductors. And these mixtures and these sort of atomic level layers, a layer upon layer, helped with that precision, and then that would have an effect on the sort of properties of the semiconductor?

**Russell Dupuis**
Yes, that's correct. Today, all of these visible LEDs we use are composed of, maybe in some cases, hundreds of layers, but typically at least five or six different materials composed specially for the design of this particular LED structure. And in many cases, those layers are only a few atomic layers thick, so on the order of 10 or 20, angstroms, or two or three nanometres. So precision is important. And of course, uniformity is important at that scale. So being able to make large area, highly uniform, thin films on the order of a single atomic layer efficiently with low cost and high yield is a critical factor in the cost, that's dramatically changed in how expensive an LED is. Blue laser pointers used to be, you know, $100 and now they're sort of almost throwaway items, they are so ubiquitous and relatively cheap.

**Sue Nelson**
And this is a key thing here, as you say, is that it could be scaled up. When you're describing it in terms of size, and then having that precision on such a large scale, which you need to make everything commercial, even now, I mean, considering that was over 40 years ago, I mean, that's incredible that it could be done. And of course, it allowed such enormous change. You must be so proud in terms of what's happened as a result of this and your role in the LED innovation?

**Russell Dupuis**
I'm obviously very proud of that. And I have a lot of people to thank, one of the most important in my life, technically of course, was my PhD advisor Professor Nick Holonyak, who as you know is-

**Sue Nelson**
Yes, the Godfather of LEDs.

**Russell Dupuis**
And literally, I think people have misinterpreted the value of his work over the course of many years because, while Nobel Prizes have been given for the heterostructure, for example, semiconductor heterostructure and more recently for the blue LED development, none of that would happen without Nick's, Professor Holonyak's, work on alloy semiconductors, on compiling three elements to make a semiconductor, or four elements to make a semiconductor in a controlled way to control the electronic properties of the material. And that so called ternary quaternary innovation was entirely his. Without that set of innovations, none of these devices would be here today. So, his fundamental work in the 1960s and early 70s were the critical ones in getting us where we are today.

**Sue Nelson**
I must admit, I did enjoy talking to him and he just casually mentioned that he was 92. It's astonishing, because I hope I'm as mentally competent at 92 as when I'm 70, let alone 92. Was he fun to work with?

**Russell Dupuis**

Oh, yes. Nick was very personable, he was one of us, or we were one of his children almost. He was a kind of hands-on Professor. He actually would eat his lunch in the laboratory. Occasionally he would actually get involved in an experiment and physically roll up the sleeves and gets some chemicals ready and etch some crystals and then cleave them and then the students would take over. He would come in every morning at 7am and wouldn't leave until 4:30pm, to go home and read the New York Times, read some more journals, start writing papers. I'd come in the next morning and the paper was written, you know, he was 100% involved both as a director of what's going on and as a participant. And I think, from my personal experience, most of his students became so enamoured with him as a person that we think of him as our godfather and technical godfather for sure.

**Sue Nelson**
It sounds like working with Holonyak was one of, you know, one of your many probably career highlights. What would you say, what is it about engineering that, you know, still gives you a thrill?

**Russell Dupuis**
Engineering, as you know, is very much applied fundamental knowledge, both from the physics community and the chemistry community, even mechanical environments that Archimedes and others worked on. But the unique feature I think is, it is fundamental knowledge applied to practical problems. So, engineering advances humanity when it's done properly. When you think about moving from the Stone Age to the Bronze Age, to the Steam Age, and beyond, a lot of those advances are based on understanding Mother Nature and applying that understanding to a practical problem. And that's what engineers do. Whether we're talking about biomedical engineering, or chemical engineering, or material science or electrical engineering, these are disciplines that are seeking to improve the human condition, in most cases. I think there's only, in my view besides medicine, engineering is the primary field for advancing the human condition. I think for young people, if they have an interest in math and physics and applying those things to those technologies and ideas to better humanity, it's one of the best careers you can use to contribute to humanity.

**Sue Nelson**
Russell Dupuis. So far, all three winners I've spoken to have been Americans and all three graduated from the University of Illinois. The other two winners, however, are from Japan and both shared the Nobel Prize for Physics in 2014 for, and I quote, "the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources." Electrical engineer Professor Isamu Akasaki, an academic who later founded the Akasaki Institute in 2006, upgraded the MOCVD technology further. And from this innovation, Shuji Nakamura of the Nichia Corporation made first blue LED in 1979.

**Shuji Nakamura**
This is more than 100 times brighter than Professor Akasaki's developed LEDs. Then in 1992 our whole company started the commercialisation of high brightness blue LEDs. Also, we developed the first high brightness green LEDs in 1995. It was at the same time the company started commercialisation.

**Sue Nelson**
And the important bit here is, because we now had blue light LEDs, you could actually make white LEDs. I don't think most people would think "oh, how did that happen?" but the human eye can see a combination of blue and yellow light, and blue and the yellow light made the white light?

**Shuji Nakamura**

Yes in 1995 we started selling white LEDs, because initially we started selling the blue LEDs since 1993, and then a cell phone company contacted our company to make a white LEDs for the backlight of the cell phone LCD screen.

**Sue Nelson**
I must admit, I think most people, particularly young people today don't realize that it wasn't that long ago when the only display on a mobile phone was in green light?

**Shuji Nakamura**
Yes. That is the same as a [indistinct], just a cold cathode illumination. It's terrible no?

**Sue Nelson**
It is. You're right. It's hard to imagine that we take all these white LEDs for granted so much.

**Shuji Nakamura**
Yeah. So, our company was also making phosphor, so we selected yellow phosphor to emit the yellow emission. So, using blue LED excited the yellow phosphor. And we can make white LEDs by mixing yellow and blue, in particular, white, in 1995.

**Sue Nelson**
And the rest, as they say, is history. It's a part of our lives. It's something that a younger generation completely take for granted, because that's all they've grown up with. Congratulations on being one of the winners of the Queen Elizabeth Prize. It's fascinating to hear about the different developments that have led to it, it shows that it's teamwork, it takes time, you build on the work of others and improve it. And that's how engineering works. How are you feeling right now? I know all of you are very eminent and have won various prizes. I mean, you've won the Nobel Prize. How do you feel about getting this award?

**Shuji Nakamura**
This award is a teamwork award. So, I'm very happy for my other colleagues because Nick Holonyak developed the first visible LEDs, also, Russel Dupuis developed the MOCVD, because MOCVD is most important to [indistinct]. We have to use MOCVD. Also, George Craford developed the highly efficient red and yellow LEDs. When I started the blue LED research in 1989 my dream was to come over to Hewlett Packard, George Craford. That is the reason I was thinking about how to make white LEDs,not blue LEDs. Also, my colleague Professor Akasaki. So basically, all of the teamwork, so all of the people contributed to this solid-state lighting. So, I am very happy together with my other colleagues.

**Sue Nelson**
Professor Shuji Nakamura. It's lovely to hear how each Queen Elizabeth Prize for Engineering winners are all so keen to pay tribute to each other. And the fruits of their innovations continues to expand as researchers are working on increasing the power of LEDs that emit UV light so that they can be used to sterilise the air in rooms, something that would be especially useful during a pandemic. And that's it for our special 2021 winners edition of the Queen Elizabeth for Engineering's Create the Future podcast. I hope you've enjoyed it.