IOP Institute of Physics **Dielectrics and Electrostatics Group**

NEWSLETTER

AUTUMN-WINTER 2023

Merry Christmas and Happy New Year!

Committee

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Co-opted members:
Dr. Nicolas Green, MInstP
Dr. Adnan Mehonic, MInstP
Dr. Jeremy Smallwood, CPhys FInstP

Members' Corner

We are pleased to announce the establishment of a platform in our Newsletters for Group members to share any of their own professional experience, that might be of interest to the dielectrics and electrostatics community. Contents can be career- or research-related. If you would like to contribute an article to any future issue of our Newsletters, please do not hesitate to contact our secretary, Dr. Mina Mortazavi, by email at mina.mortazavi@beds.ac.uk. As a start, our committee members Dr. Jeremy Smallwood and Dr. Ho-Kei Chan have each contributed a commemorative article to the current issue of our Newsletters. Jeremy shares his twenty five years of professional experience in the field of electrostatics consulting, while Ho-Kei presents a general theory of space-charge conduction that he initiated twenty years ago. It is hoped that this platform could serve to foster academic interactions and research collaborations among our members.

Upcoming Event: Memristor 2024

Memristor 2024, to be hosted by the IOP's Dielectrics and Electrostatics Group, is a one-day event on 26th January 2024 at IOP King's Cross, aimed at uniting researchers intrigued by memristive technologies. Over the past two decades, memristors have captivated a diverse range of research communities, including mathematicians, solid-state physicists, material scientists, electrical engineers, and more recently, computer scientists and computational neuroscientists. To date, memristive technologies remain highly relevant, offering solutions to various challenges posed by the current limitations of CMOS electronics. This conference spans topics from new materials and device designs to systems and algorithms, aiming to foster cross-disciplinary dialogue from fundamental physics to practical applications. This approach seeks to link researchers across the field, encouraging the emergence of new, productive collaborations in memristor research. For further information please visit the conference's website.

Upcoming Event: Dielectrics 2024

The IOP's Dielectrics & Electrostatics Group is hosting its biennial Dielectrics conference at the Institute of Physics, London UK from the 16th to the 18th of April 2024 to explore the ever-expanding areas of dielectrics research and applications. The conference welcomes contributions from physicists, chemists, materials scientists, engineers and technologists. The theme of the conference is "Ferroelectrics and dielectrics from nanoscale to devices", and the conference will include all areas of study pertinent to dielectrics. We welcome contributions in a number of areas such as: (1) modelling and theory, (2) advanced characterisation, (3) dielectrics for devices, and (4) ferroelectrics. Contributions from both academia and industry, covering areas in physics, chemistry, materials science, engineering and technology, are welcome. For further information please visit the conference's website (Abstract submission by 12th January 2024).

Next page: more upcoming events

Upcoming Event: 12th Conference on Broadband Dielectric Spectroscopy and its Applications

The 12th Conference on Broadband Dielectric Spectroscopy and its Applications will take place at Reitoria da Universidade Nova de Lisboa, Portugal, from the 1st to the 6th of September 2024. Registration will be available from 4th March 2024. For further information please visit the conference's website or contact the organizers by email at bds2024org@campus.fct.unl.pt.

Upcoming Event: Dielectrophoresis 2024

The fifth instalment of the bi-annual dielectrophoresis conference will be hosted at University College Dublin, Ireland, from the 1st to the 3rd of July 2024 (The conference's website is under construction). Abstract submission will be open in early 2024. Topics to be covered include (1) fundamentals of AC Electrokinetics, (2) biological applications (including disease diagnostics and therapeutics), (3) impedance and dielectric spectroscopy, (4) dielectrophoretic manipulation, (5) insulator dielectrophoresis, (6) liquid dielectrophoresis, (7) electrowetting, (8) droplet dielectrophoresis, (9) nanoscale dielectrophoresis, (10) dielectrophoretic separation, (11) dielectrophoretic assembly, (12) electrorotation and electroorientation, and (13) electroporation.

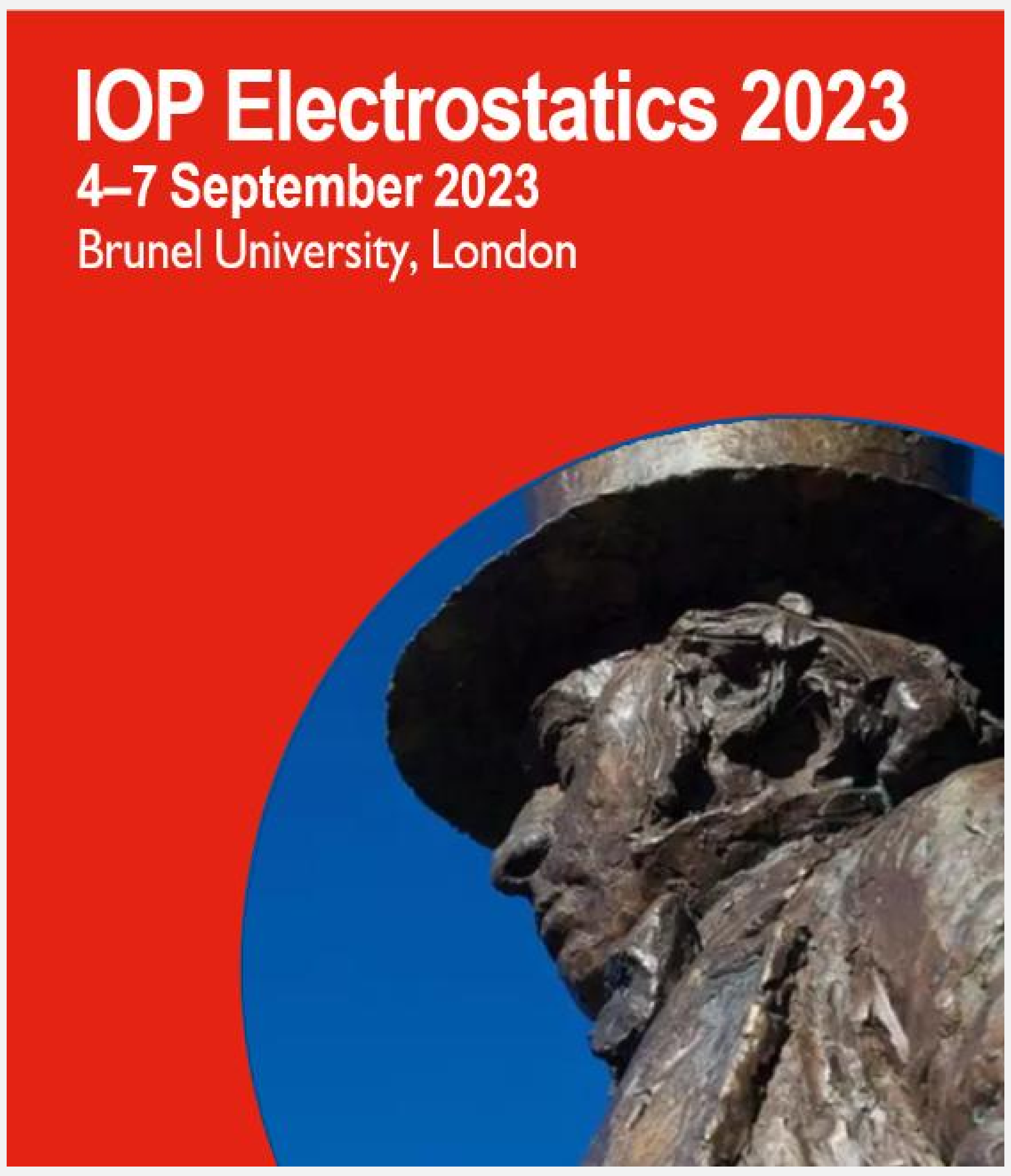
Stay tuned for more information!

Nominations for Group Prizes

We invite nominations of early-career researchers for two Group prizes by 20th October 2024. These prizes, each of which is up to £100 and includes a certificate, reflect the complementary interests of the IOP's Dielectrics and Electrostatics Group in both academia and industry.

- The Mansel Davies Award for outstanding contributions to dielectrics. It honours the contribution of Prof. Mansel Morris Davies to the Dielectrics Discussion Group (1968 - 1974).
- The John Chubb Award for outstanding contributions to experimental electrostatics. It honours the contributions of Dr. John Norman Chubb to the understanding of electrostatics.

For more information please visit the Group's website.



Past Event: Electrostatics 2023

The International conference, "Electrostatics 2023", was held in Brunel University London for four consecutive days between the 4th and the 7th of September 2023. This quadrennial conference was organized by the Dielectrics and Electrostatics Group of the UK's Institute of Physics (IOP). The conference brought together many experts from both academia and industry worldwide in one place.

Electrostatics 2023 welcomed experts and keynote speakers and witnessed more than 70 scientists, scholars, and early career researchers to present their recent discoveries, research developments and advancements. (To be continued)

Past Event: Electrostatics 2023 (continued)

There were thirteen oral sessions and two poster sessions over the four days. The conference started with a welcome address by the conference chair Dr. Nadarajah Manivannan, followed by the Bill Bright Memorial talk delivered by Prof. Balachandran on “Non-Thermal plasma for medical applications”. The delegates came from all over the word; UK, France, Germany, Japan, USA, Canada, India (Bharat), Hungary, Turkey, Russia, Poland, China, Solvenia, South Korea, Netherlands, Algeria, Latvia, Czech Republic and Austria. Two student prizes were awarded; one for the best poster and one for the best Oral. The winners were each awarded a certificate and a cash prize. A total cash prize of £250 was sponsored by Ossila. The winners were Juan Carlos Sobaizo from the Institute of Science and Technology Austria for his oral presentation entitled "A Triboelectric series of identical materials" and Jana Sklenářová from UCT Prague for her poster presentation entitled "Sorting of Plastic Waste Utilising Triboelectrification and Subsequent Electric Field Separation".

In addition to networking breaks and lunches, there were a BBQ dinner on Monday, 4th September and a conference dinner on Tuesday, 5th September. The conference dinner was held in Watersedge, Cowley, where conference delegates gathered and enjoyed the warm and casual atmosphere. There was an Indian Music live concert performed during the lunch of Tuesday, 5th September, which offered a smooth and charming environment to the conference. It was a truly successful event and everyone enjoyed and benefited one way or another.

Welcome address by
Dr. Nadarajah Manivannan

Poster session

Conference dinner

Group Photo by the statue of
Isambard Kingdom Brunel

(Next: commemorative article by Dr. Jeremy Smallwood)

25 Years in Electrostatics Consulting
by Jeremy Smallwood

Back in early 1998 I finally made the decision I had been thinking about for some time. I had been working for a few years in Leatherhead, and my family was living seventy miles away in Southampton. The 140 m round trip daily had taken its toll, and so I had decided to live somewhere nearer during the week – but that in turn had also taken its toll in different ways. It was time to do something different. I moved back to Southampton, and set up my Company, Electrostatic Solutions Ltd, in preparation. I was planning to offer electrostatics consulting, training and R&D services to industrial clients. Running my own business seemed at the same time exciting and daunting – as a keen birdwatcher, I felt like a fledgling launching off a cliff, learning to fly on my way down!

I'd written a business plan – it had the desired effect when I visited my bank to open an account. The Bank Manager was supportive. "I haven't a clue what you do, Jeremy", he said, "but it seems well thought out and impressive". Filling in the bank's computer forms to open the account, we found there was no relevant category of business to represent mine. The nearest we could get was "Electrostatic precipitator manufacturer" so that's what the computer recorded.

I knew I could technically do the work I expected to get, I'd been doing it for over ten years. I thought I had a reasonable idea of what sort of customers I would have. The electronics industry would be the first target. Any company manufacturing or handling electronic products needs to have electrostatic discharge (ESD) safe manufacturing areas to build their product. This was something I knew about; I'd been working with BSI and IEC groups writing standards on ESD control for several years.

Similarly, process industries handling flammable materials such as solvents or fine dusts need to take care of electrostatic fire and explosion risks. I could work from home, at least at first. I bought the basic instruments I would need with some savings I had put by. I already had a computer and software that would take care of report writing and basic accounting.

The reality of starting trading was a complete shock. Suddenly, no work coming in or foreseeable. Fortunately, I was on good terms with my old employer, who asked me to take on some of my old activities as a subcontractor. This was a real lifesaver, and gave me a basic income for a year or two. (To be continued)

Author's bio:

Dr. Jeremy Smallwood designed electronic instruments in industry before completing his PhD in electrostatic discharge ignition studies as a Research Fellow at Southampton University. In the mid 1990s, he worked as Electrostatics Section Leader at ERA Technology Ltd. In 1998 he formed Electrostatic Solutions Ltd, providing electrostatics consultancy, training and R&D services in static control in the electronics industry, electrostatic hazards, measurements and applications. He works with British and IEC standards. He has received the 2010 ESD Association Industry Pioneer Award, the International Fellow Award at Electrostatics 2017, and the Stig Lundquist Award at Electrostatics 2022. Jeremy has over sixty publications in the field of electrostatics and ESD control and is author of "The ESD Control Program Handbook" published by Wiley in 2020.

25 Years in Electrostatics Consulting (continued)
by Jeremy Smallwood

I found that my business plan was at best a plausible work of fiction. The hard truth is that no matter how good you are at what you do, if you can't find someone who wants to pay you to do it, you're sunk. Selling consulting is not like selling pizzas. If a pizza looks good, tout it round and you'll get a few buyers. People won't buy consultancy unless they've got a problem to solve, and it's enough of a problem to want to do something about it.

No-one expects to have an electrostatics problem so you can't interest them on the basis that they might in the future! I realised there was a real problem – not many people would be looking for an electrostatics or ESD control consultant. If they did, they would have as much difficulty finding me as I would finding them. Marketing would be more difficult for me than the technical problems I'd face. There was one other problem – I didn't have much cash to pay for adverts, directory entries and the like.

So, my strategy was to find low cost ways of getting my name known. Informative articles in trade magazines that potential clients might read would be one option. The problem is, potential clients might be in many different industries as electrostatics problems arise in many types of processes. I would have to restrict myself to a few likely areas. Another option was to make informative presentations at trade events. Thirdly, the internet and Google were becoming more widely used. I realised I could have a web site that would be available to be found world-wide, for the price of a single UK region entry in the "Yellow Pages" advertising directory. I found that no strategy I could think of would generate projects in the short term – marketing produced only medium- and long-term results. Even after twenty five years I find that is true – the only exception is to book a holiday – urgent enquiries seem to flood in as if by magic just as I'm about to go away!

Starting a consulting business has another problem – cash flow. It all flows out and for some time, very little flows in. To illustrate why, let's say each week I get ten enquiries (I should be so lucky!). Out of talking to those enquirers, maybe two might be sufficiently interested to require a proposal. After I've sent them a proposal, a proportion (let's say 50%) will opt to go ahead – but it might take them between a couple of weeks and a couple of years (yes really!) to make this decision.

Jeremy demonstrating static electricity in ESD seminar 2002

After I've received their order, it could take several weeks to arrange a site visit, do the work and write a report. Even if I then invoice the client immediately it's at least 30 days before they pay, and for some, much longer. At first, I was mainly talking to people and trying to get orders for quite a long time before they started to flow. Then, there was a considerable delay before money started to come in. One has to survive that period to reach the state where one is living off the earlier income while generating the income which will eventually come in sometime over the next six months or more.

I had naively thought the electronics industry would be the easiest sector to get business – after all, any electronics company has to set up a static safe for handling or assembling ESD sensitive products and components. In practice I didn't get a single project for at least 2 years. Companies were used to getting their advice and

(To be continued)

25 Years in Electrostatics Consulting (continued)
by Jeremy Smallwood

training often free of charge from the suppliers of ESD control equipment. Actually, they were not interested in electrostatics – they just wanted to know if they had done enough, or at best that they were compliant with an ESD control standard. Many were somewhat sceptical about ESD damage anyway – as far as they were concerned, they never experienced a problem.

At last, I found a niche and a way forward – I had been involved in writing ESD control standards for some years. I offered training courses on principles and practice of ESD control, setting up an ESD control program according to the standards and related measurements on ESD control equipment. As most existing ESD courses were very basic, this course found a market, had little competition and was something I could "sell" in a conventional manner. I also found my delegates came back to me with questions, and some for advice to help them improve their ESD control facilities. My name became better known, my reputation started to build and business improved. I also focussed my web site on electronics industry information and issues, and that started to draw in enquiries.

The web site also led to other unforeseen types of enquiries. (Projects sprout like mushrooms from unexpected places). One area I had not expected was in helping companies who had problems with electrostatic shocks to personnel. A common example is feeling a shock on touching a door knob after walking across a floor. Most of us of course are familiar with these types of shocks, but they are usually low level and suffered in silence. Occasionally they cause enough of a problem to be acted on. For offices or retail premises, there may be concern over discomfort to staff or customers. One problem for me as a consultant is that I can't offer a solution, which is what the customer really wants. In a large proportion of the cases, the source of the static can be shown to be walking on a particular floor covering, or sometimes use of a particular chair or other furniture. Sometimes the situation is exacerbated by the presence of a particular feature that encourages shocks. In one case, the architect had provided a nice glass floor which charged people up quite highly, and provided beautiful stainless-steel banisters and other features which inadvertently made sure they would get a shock when they touched them. My role in these cases is to find out and confirm (with measurements) what are the key factors at play and advise the customer what they could change to improve the situation. Unfortunately, these changes can be difficult or expensive. Some of these cases can have a health and safety aspect – in one case a tile floor was laid in a kitchen which caused the chefs to charge up and get shocks from touching the stainless steel cooking pans and appliances. There was a real and continuous risk of hot liquid or food spillage as a result.

Static shocks at a ticket barrier

Another common area for shocks to personnel was at the entry to car parks. A car will generate charge as it rolls – normally this is dissipated through the tyres and road surface quite quickly when it stops. But, if the car stops on a very high resistance floor material (e.g., epoxy or asphalt) it can hold its charge for some time. If the driver leans out to take a ticket from the barrier machine, they can get a strong shock. Typically, the customer complains to the car park operator, and the operator to the ticket machine manufacturer, that the machine is giving people shocks. The machine manufacturer fights back pointing out that the machine is earthed and can't possibly be the source of shocks. Analysing the situation shows the problem, and often confirms

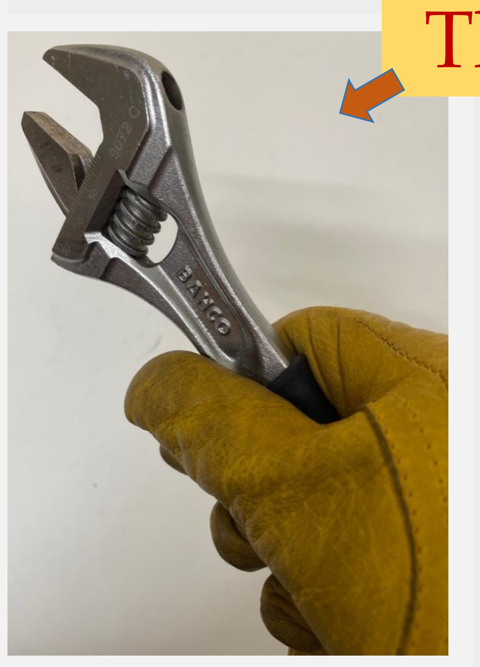
(To be continued)

25 Years in Electrostatics Consulting (continued)
by Jeremy Smallwood

that it started after a refurbishment program in which the floor covering was replaced with a highly insulating cover material like epoxy.

Another major area for ESD control is, of course, the handling of flammable liquids or powders, or energetic materials (pyrotechnics or explosives) in manufacturing processes. My PhD was in ignition studies and so I've had an interest in this for many years. Often this type of project is about evaluation of risks for ATEX and DSEAR purposes. Sometimes, unfortunately, it has been in response to a fire or explosion incident. Alongside this work, I've had occasional projects helping to write industry guidance on electrostatic hazard avoidance.

Fires or explosions are often caused by small changes made that were not foreseen to be a likely cause of a problem. There may be coincidence with one or more unexpected factors. Often it is an activity that has been performed many times before and is thus perceived to be safe. In one case, an engineer opened a pipe which was not expected to have flammable material present, but when he did so a flammable liquid unexpectedly emerged. He reacted to close a metal shut off valve with a handheld metal spanner – the liquid vapor ignited. Unfortunately, although he was adequately earthed using antistatic footwear on a static dissipative concrete floor, he had worn leather gloves due to the cold weather. Experiments showed that the rubber handled metal wrench held in the gloved hand could charge up under cold dry conditions to cause a spark.


The glove and wrench that caused a flash fire

In another case, unexplained bin fires were occurring in a manual small part moulding process. There were no flammable atmosphere Zones present. Operators were using a aerosol mould release agent, and disposing of the cans in plastic bins. The cans could leak propellant (likely butane) into the bin, which is where it would stay, being heavier than air. The operators also cut highly charged plastic sprue cut from the mouldings and threw it into the bin. The highly charged material induced voltage differences between aerosol cans. Every now and then two cans would spark between them and if enough butane was present, a fire would ignite.

Occasionally the chance would come to be part of a larger R&D project such as a European project. The first project in which I worked with my previous employer ERA Technology Ltd was one such, the ELREC project on electrostatic separation of materials for recycling. Projects like this are unusual in giving ongoing work for a period of time, in contrast to the usual one or two days. Another example is the SPABRINK European project in which I participated with the University of Southampton. This project was trying to make a low power bill-board type display using electrostatics to pin coloured powders in place, after printing an image in powder onto to a large white background sheet electrode to form the intended picture. An interdigitated electrode gave strong electrostatic fields that held the powder in place by dielectrophoretic forces. The picture could be erased by switching off the field, and a new picture subsequently printed over the electrode. The old powder was collected for recovery.

Looking back it had taken about ten years before I stopped feeling like a startup. I rarely know where the next few months work will be coming from but these days I have more confidence that it will come. In 2023, industrial electrostatics continues to give me a life full of variety and interesting technical challenges.

(Next: commemorative article by Dr. Ho-Kei Chan)

20th Anniversary of a General Theory of Space-Charge Conduction
by Ho-Kei Chan

In 2003, I worked on a theoretical project with the aim to understand the mechanism(s) of polarization offsets observed experimentally for compositionally graded ferroelectric films [1,2]. Such offsets refer to vertical shifts of the observed *D-E* hysteresis loops. Any such offset develops like the typical charging-up of a capacitor, changes in direction if the compositional gradient of the ferroelectric film is inverted, and increases in magnitude monotonously with the amplitude of the applied sinusoidal field. On 27th July 2003, four days before the end of my position as a research assistant, I derived a nonlinear expression for space-charge conduction in solid dielectrics [3], and then plugged the expression into my simulations. The experimental features described above were all reproduced [3,4] and, to my surprise, the simulations have also revealed a memristive-like "current density - electric field" relation for such systems [3]. Eureka!

Twenty years on, my collaborators and I have used this conductivity expression to study the origin of imprint effects (i.e. horizontal shifts of *D-E* hysteresis loops) in ferroelectric thin films [5], further justified the assumptions behind the derivation of this expression [6,7], generalized the expression into a theory that also describes processes of electrical diffusion [7,8], and used the theory to predict possible Seebeck effects in solid dielectrics [8]. To commemorate our Eureka moment on 27th July 2003, I have organized decennial birthday parties for this conductivity expression, on 27th July of 2013 and 2023, respectively:

In this commemorative article, I take the opportunity to review the fundamental aspects of our theory, which takes into account the cooccurrence of Ohmic and space-charge conduction and the copresence of p-type and n-type charge carriers, as different from the conventional models of Ohmic conduction and space-charge-limited conduction. (To be continued)

Author's bio:

Dr. Ho-Kei Chan (陈浩基) is an Associate Professor of Physics (2016 - present) at the Harbin Institute of Technology, Shenzhen (China). He obtained a 1st Class BSc in Engineering Physics in 2002 from the Hong Kong Polytechnic University (Hong Kong, China) and a PhD in Physics in 2007 from the University of Manchester (UK), followed by post-doctoral appointments at the Hong Kong Baptist University (Hong Kong, China), Trinity College Dublin (Ireland), and the University of Nottingham (UK). Ho-Kei's research interests include electrostatics theory, packing problems, and conduction problems.

20th Anniversary of a General Theory of Space-Charge Conduction (continued)
by Ho-Kei Chan

For any macroscopic system, the conduction-current density $\vec{J}_{\text{cond}}$ and the electric field $\vec{E}$ are related to each other via the electrical conductivity σ as follows:

$$\vec{J}_{\text{cond}} = \sigma \vec{E}$$

Consider the copresence of p-type and n-type charge carriers. For each type of carriers, let C be the number concentration, μ the absolute value of the carriers' mobility, and e the elementary charge. The total electrical conductivity of the system is given by

$$\sigma = eC_{\text{p}}\mu_{\text{p}} + (-e)C_{\text{n}}(-\mu_{\text{n}})$$

for $\mu_{\text{p}} > 0$ and $\mu_{\text{n}} > 0$. (To be continued)

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20th Anniversary of a General Theory of Space-Charge Conduction (continued)

by Ho-Kei Chan

Consider two limiting cases: In the case of Ohmic conduction with zero space-charge, the concentration of either carrier type is equal to the intrinsic concentration C_{in}:

$$C_{\text{p}} = C_{\text{n}} = C_{\text{in}}$$

The corresponding Ohmic (or intrinsic) conductivity is given by

$$\sigma = eC_{\text{in}}(\mu_{\text{p}} + \mu_{\text{n}}) \equiv \sigma_{\text{o}}$$

In the case of space-charge-limited conduction, the intrinsic concentration vanishes such that there does not exist any Ohmic conductivity. Electrical conduction occurs because charge carriers of a single type are injected from the electrodes. If, for example, only p-type carriers are injected, the charge density is equal to

$$eC_{\text{p}} = \vec{\nabla} \cdot \vec{D}$$

according to Gauss' law. The corresponding space-charge conductivity is given by

$$\sigma = \mu_{\text{p}}[\vec{\nabla} \cdot \vec{D}] = \sigma_{\text{sc}}$$

If there exist both Ohmic and space-charge conduction, is the total conductivity σ equal to a superposition of the Ohmic conductivity σ_{o} and the space-charge conductivity σ_{sc}?

To address this problem, we express the concentration of each carrier type as a perturbation from its intrinsic value:

$$C_{\text{p}} = C_{\text{in}} + \Delta p \quad \text{and} \quad C_{\text{n}} = C_{\text{in}} + \Delta n$$

for $C_{\text{p}} \neq C_{\text{n}}$ in general, such that the generally non-zero space-charge density is given by

$$\vec{\nabla} \cdot \vec{D} = eC_{\text{p}} + (-e)C_{\text{n}} = (\Delta p - \Delta n)e$$

The total conductivity can then be expressed as

$$\sigma = \sigma_{\text{o}} + (\mu_{\text{p}}\Delta p + \mu_{\text{n}}\Delta n)e$$

To solve for the unknowns Δp and Δn, two constraints are needed. If the space-charge density $\vec{\nabla} \cdot \vec{D}$ is a known quantity, there remains one missing constraint.

Here we propose that the mass-action relation between the concentrations of the two types of carriers is the missing constraint we are looking for. Consider the following generation and recombination of carriers:

$$\text{valence electron} \leftrightarrow \text{hole} + \text{free electron}$$

Since holes are by definition missing valence electrons, we have

$$\mathrm{d}C_{\text{v+p}} = \mathrm{d}\left(C_{\text{v}} + C_{\text{p}}\right) = 0$$

At steady states, the condition of detailed balance implies

$$K_{\text{generation}} C_{\text{v}} = K_{\text{generation}} \left(C_{\text{v+p}} - C_{\text{p}}\right) = K_{\text{recombination}} C_{\text{p}} C_{\text{n}}$$

where, for the specific case of zero space-charge, we have

(To be continued)

20th Anniversary of a General Theory of Space-Charge Conduction (continued)

by Ho-Kei Chan

$$K_{\text{generation}}\left(C_{\text{v+p}}-C_{\text{in}}\right)=K_{\text{recombination}}C_{\text{in}}^{2}$$

From the above conditions, we obtain the following generalized mass-action relation

$$C_{\text{p}}\left[(1-\alpha)C_{\text{n}}+\alpha C_{\text{in}}\right]=C_{\text{in}}^{2}$$

where the fraction of intrinsic carriers

$$\alpha\equiv\frac{C_{\text{in}}}{C_{\text{v+p}}}$$

is a material property. Consider the following relative rate of carrier generation:

$$K'\equiv\frac{K_{\text{generation}}}{C_{\text{v+p}}K_{\text{recombination}}}=\frac{\alpha^{2}}{1-\alpha}$$

From this relation between K' and α, we obtain

$$\alpha=-\frac{K'}{2}+\sqrt{\left(\frac{K'}{2}\right)^{2}+K'}\approx\begin{cases}0, & K'\to 0 \quad \text{(insulators)}\\ 1, & K'\to\infty \quad \text{(conductors)}\end{cases}$$

and the following mass-action relation for dielectric insulators

$$\lim_{\alpha\to 0}C_{\text{p}}\left[(1-\alpha)C_{\text{n}}+\alpha C_{\text{in}}\right]=C_{\text{p}}C_{\text{n}}=C_{\text{in}}^{2}$$

Using the constraints

$$C_{\text{p}}C_{\text{n}}=C_{\text{in}}^{2}$$

and

$$\vec{\nabla}\cdot\vec{D}=(\Delta p-\Delta n)e$$

we obtain a pair of quadratic equations for the unknowns Δp and Δn, respectively:

$$\Delta p^{2}+\left[-\frac{1}{e}\vec{\nabla}\cdot\vec{D}+2C_{\text{in}}\right]\Delta p+\left[-\frac{C_{\text{in}}}{e}\vec{\nabla}\cdot\vec{D}\right]=0$$

and

$$\Delta n^{2}+\left[\frac{1}{e}\vec{\nabla}\cdot\vec{D}+2C_{\text{in}}\right]\Delta n+\left[\frac{C_{\text{in}}}{e}\vec{\nabla}\cdot\vec{D}\right]=0$$

which imply

$$e\left(\mu_{\text{p}}\Delta p+\mu_{\text{n}}\Delta n\right)=\left(\frac{\mu_{\text{p}}-\mu_{\text{n}}}{2}\right)\vec{\nabla}\cdot\vec{D}-\sigma_{\text{o}}\pm\left(\frac{\mu_{\text{p}}+\mu_{\text{n}}}{2}\right)\sqrt{\left(\vec{\nabla}\cdot\vec{D}\right)^{2}+\frac{4\sigma_{\text{o}}^{2}}{\left(\mu_{\text{p}}+\mu_{\text{n}}\right)^{2}}}$$

At zero space-charge, i.e. $\vec{\nabla}\cdot\vec{D}=0$ and $\Delta n=\Delta p=0$, we have

$$\sigma_{\text{o}}=\pm\left(\frac{\mu_{\text{p}}+\mu_{\text{n}}}{2}\right)\sqrt{\frac{4\sigma_{\text{o}}^{2}}{\left(\mu_{\text{p}}+\mu_{\text{n}}\right)^{2}}}=\pm\sigma_{\text{o}}$$

which indicates that the $\pm$ sign above should just be a positive sign. The total conductivity of the system is then given by

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$$\sigma = \sigma_o + e(\mu_p \Delta p + \mu_n \Delta n) = \frac{(\mu_p - \mu_n)}{2}\vec{\nabla}\cdot\vec{D} + \sqrt{\left(\frac{(\mu_p + \mu_n)}{2}\vec{\nabla}\cdot\vec{D}\right)^2 + {\sigma_o}^2} \neq \sigma_o + \sigma_{sc}$$

This expression, which describes how the total conductivity depends on the difference in absolute mobilities (i.e. average mobility of the two carrier types) and on the average of absolute mobilities (i.e. mobility difference between the two carrier types), indicates that the total conductivity is *not* equal to a superposition of the Ohmic conductivity and the space-charge conductivity. At zero space-charge, i.e. $\vec{\nabla}\cdot\vec{D} = 0$, the total conductivity reduces to the Ohmic conductivity. On the other hand, in the absence of Ohmic conductivity, the above conductivity expression reduces to the conventional expressions for space-charge-limited conduction:

$$\sigma = \frac{(\mu_p - \mu_n)}{2}\vec{\nabla}\cdot\vec{D} + \frac{(\mu_p + \mu_n)}{2}[\pm\vec{\nabla}\cdot\vec{D}] = \begin{cases} \mu_p \vec{\nabla}\cdot\vec{D}, & \text{for } \vec{\nabla}\cdot\vec{D} > 0 \\ -\mu_n \vec{\nabla}\cdot\vec{D}, & \text{for } \vec{\nabla}\cdot\vec{D} < 0 \end{cases}$$

The results for these two limiting cases confirm the validity of our conductivity expression.

For cases of one-dimensional steady flow of charge in a plane-parallel setup, we have generalized the above theoretical formulation to take into account any diffusion of carriers due to the presence of a charge-density gradient or a temperature gradient. For each type of carriers, diffusion is thought of as arising from a pseudo electric field due to the presence of a pressure gradient:

$$\tilde{E}_p(x) = -\frac{1}{eC_p(x)}\frac{dP_p(x)}{dx} \quad \text{and} \quad \tilde{E}_n(x) = -\frac{1}{[-eC_n(x)]}\frac{dP_n(x)}{dx}$$

where we adopt an ideal-gas approximation to describe how the local pressure depends on the local temperature and on the carriers' local concentration:

$$P_p(x) = k_B T(x) C_p(x) \quad \text{and} \quad P_n(x) = k_B T(x) C_n(x)$$

Consider a position-dependent mobility for each type of carriers. The position-dependent diffusion-current density is given by

$$J_{diff}(x) = e[\mu_p(x)C_p(x)\tilde{E}_p(x) + \mu_n(x)C_n(x)\tilde{E}_n(x)] = -\left[\mu_p(x)\frac{dP_p(x)}{dx} + [-\mu_n(x)]\frac{dP_n(x)}{dx}\right]$$

Combining this expression with the solutions of Δp and Δn, we obtain

$$J_{diff}(x) = J_{diff,1}(x) + J_{diff,2}(x)$$

where the components

$$J_{diff,1}(x) \equiv -\frac{k_B T(x)[\mu_p(x) + \mu_n(x)]}{2e}\frac{d^2 D(x)}{dx^2} - \frac{[\mu_p(x) - \mu_n(x)]k_B T(x)}{\sqrt{\left[\frac{1}{2e}\frac{dD(x)}{dx}\right]^2 + C_{in}(x)^2}}\left[\frac{1}{4e^2}\frac{dD(x)}{dx}\frac{d^2 D(x)}{dx^2} + C_{in}(x)\frac{dC_{in}(x)}{dx}\right]$$

and

$$J_{diff,2}(x) \equiv -k_B \frac{dT(x)}{dx}\left\{\frac{[\mu_p(x) + \mu_n(x)]}{2e}\frac{dD(x)}{dx} + [\mu_p(x) - \mu_n(x)]\sqrt{\left[\frac{1}{2e}\frac{dD(x)}{dx}\right]^2 + C_{in}(x)^2}\right\}$$

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correspond respectively to diffusion due to the presence of a charge-density gradient and of a temperature gradient. Consider the concentration of space charge,

$$C_{\text{sc}}(x) \equiv \frac{1}{e}\frac{\mathrm{d}D(x)}{\mathrm{d}x}$$

and the concentration of intrinsic carriers,

$$C_{\text{in,total}}(x) \equiv 2C_{\text{in}}(x)$$

and then define an effective concentration

$$C_{\text{eff}}(x) \equiv \sqrt{C_{\text{sc}}(x)^2 + C_{\text{in,total}}(x)^2}$$

that reflects the orthogonality between $C_{\text{sc}}(x)$ and $C_{\text{in,total}}(x)$ (i.e. the intrinsic concentration, which is a material property, is not influenced by any external injection of space-charge). The diffusion-current density described above can then be expressed in a much simpler form, as follows:

$$J_{\text{diff}}(x) = -k_{\text{B}}\frac{[\mu_{\text{p}}(x)+\mu_{\text{n}}(x)]}{2}\frac{\mathrm{d}[T(x)C_{\text{sc}}(x)]}{\mathrm{d}x} - k_{\text{B}}\frac{[\mu_{\text{p}}(x)-\mu_{\text{n}}(x)]}{2}\frac{\mathrm{d}[T(x)C_{\text{eff}}(x)]}{\mathrm{d}x}$$

In a similar manner, the conduction-current density can be expressed as

$$J_{\text{cond}}(x) = \sigma(x)E(x) = \frac{[\mu_{\text{p}}(x)-\mu_{\text{n}}(x)]}{2}eC_{\text{sc}}(x)E(x) + \frac{[\mu_{\text{p}}(x)+\mu_{\text{n}}(x)]}{2}eC_{\text{eff}}(x)E(x)$$

The above expressions, which are strikingly similar in form, imply that the position-independent total-current density is equal to the following determinant:

$$J_{\text{total}} = J_{\text{cond}}(x) + J_{\text{diff}}(x) = \begin{vmatrix} -\frac{[\mu_{\text{p}}(x)+\mu_{\text{n}}(x)]}{2} & 0 & -\frac{[\mu_{\text{p}}(x)-\mu_{\text{n}}(x)]}{2} \\ -T(x)C_{\text{sc}}(x) & k_{\text{B}}\frac{\mathrm{d}}{\mathrm{d}x} & T(x)C_{\text{eff}}(x) \\ -T(x)C_{\text{eff}}(x) & \frac{eE(x)}{T(x)} & T(x)C_{\text{sc}}(x) \end{vmatrix}$$

By setting this total-current density to be zero for a general electrostatic condition, we have predicted that, in the presence of space charge, the Seebeck coefficient of a homogeneous plane-parallel dielectric capacitor could go beyond the upper limit of the linear response regime described by Onsager's reciprocal relations:

$$S \in \left[\frac{k_{\text{B}}}{e}, \frac{2k_{\text{B}}}{e}\right]$$

where this application of our theory is discussed in detail in Reference [8].

Looking forward, it is hoped that this article would inspire experimental tests of our theory in the near future. To conclude, I would like to thank my collaborators Prof. Franklin G. Shin (of the Hong Kong Polytechnic University, now retired), Dr. Chi-Hang Lam (of the Hong Kong Polytechnic University), Prof. Yan Zhou (of the Chinese University of Hong Kong, Shenzhen) and Prof. Dahai He (of Xiamen University) for so many insightful discussions over the years.

(End of Newsletter)