Enabling dark injection SCLC to characterize trapping in OLED charge transport layers

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ABSTRACT

Dark injection space charge limited current (DI-SCLC) is used to evaluate hole transport layers (HTLs) with different trap concentrations resulting from different HTL purities. We show that by varying the measurement duty cycle DI-SCLC can determine in a sample with significant trapping the trap-free mobility and the mobility with traps.

1. INTRODUCTION

Good charge transport in OLEDs is important for the development of OLEDs with low driving voltages and good power efficiency. Charge trapping is detrimental to good transport in organic semiconductors because these immobile charges shield the external electric field.

It is important to know the role of traps in charge transport because often these traps are from impurities. Therefore, charge transport can be improved with the removal of impurities, but it is first good to know how the pure material will perform prior to trying to improve the material via purification. A method which can characterize the charge transport that is insensitive to the charge trapping would be useful to find this intrinsic limit. Therefore, one can tell if the material has the potential to be a good transport layer and to perform well before investing time and effort to further purify the material. However, one also needs a method that is sensitive to the charge trapping to determine how much traps affect impure material, which is necessary to be able to quantify the extent of trapping in the material.

In this paper we show new way to use dark injection space charge limited current (DI-SCLC) to measure the charge mobility (μ) both in the presence of charged traps and without charged traps. This method is a powerful tool to both determine the intrinsic mobility of the material as well as show how the real material with traps performs.

2. Experimental

In this experiment we examine the charge transport of two batches of different purities of a proprietary Novaled hole transport layer (HTL) NHT-174 (99.90% purity and 99.39% purity as measured by HPLC). In order to evaluate the charge transport hole-only devices are created by thermal evaporation. These devices have a layer structure of ITO (100 nm)/ NHT-25:NDP-9(10 nm)/ NHT-174 (700nm)/ NHT-25:NDP-9 (10 nm) / Au (10 nm) /Al 100 nm). The 10 nm layers of NHT-25:NDP-9 (NHT-25 and NDP-9 is a Novaled HTL and p-dopant respectively) are necessary to ensure ohmic contacts to the ITO anode and Au/Al cathode.

The IVs of the devices are measured and the mobility is determined by DI-SCLC and Admittance Spectroscopy (AS). DI-SCLC measurements made by measuring the current transient due to a square wave voltage pulse from 0V to the pulse voltage (V_{pulse}). This current transient can be used to find the transit time of the device which can in turn used to determine μ[1]. In this experiment the voltage pulse is repeated at a rate of 1 kHz and V_{pulse} and the duty cycle (the percentage of time the device is driven at V_{pulse}) is varied. Mobility is determined in Admittance spectroscopy from Capacitance vs. frequency traces and is described in detail in ref [2].

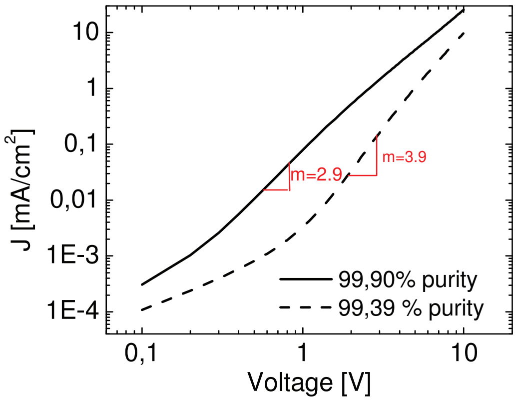

Fig. 1. Current density (J) vs. voltage characteristics of the NHT-174 hole only devices with different purities. “m” shows the max slope of each curve.

3. Results and discussion

Figure 1 shows that the J-V characteristics are different for different purities. The maximum slope (m) of this log-log plot can be related to the trapping energy and trap density [3]. Therefore, we can conclude that the sample with 99.90% purity (m=2.9) has less trapping than the sample with 99.39% purity (m=3.9).

To further investigate the charge transport we investigated the mobilities (μ) of the samples by DI-SCLC and AS. Figure 2 shows the log(μ) vs $E^{1/2}$, where $E^{1/2}$ is the square root of the electric field. Here the data all show the predicted a Poole-Frenckel dependence where there is a linear dependence of log(μ) vs. $E^{1/2}$ [1].

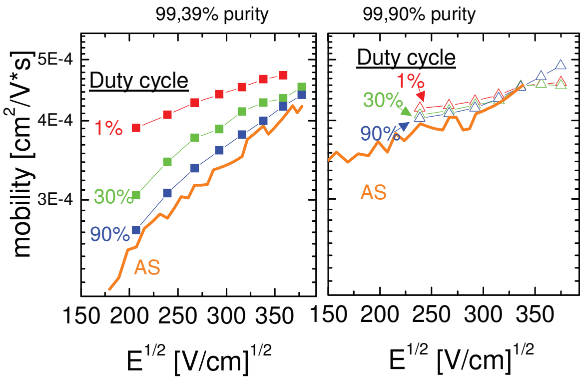

Fig. 2. μ vs. $E^{1/2}$ measured by AS and DI-SCLC. The DI SCLC was measured at duty cycles of 1%, 30% and 90%.

The E-field dependence of the AS curves is very different for the 99.39 % purity and 99.90 % purity samples, most likely due to the higher amount of trapping in the lower purity sample. Trapped charges decrease the measured mobility because they screen the applied electric field resulting in a lower effective electric field acting on the free charge carriers. This causes the lower observed μ in the less pure device.

Interestingly, the traps in the low purity sample also result in the larger electric field dependence of μ. This is a result of the number of charged traps (n_{trap}) being fixed while the total number charges ($n_{total}= n_{trap}+n_{free}$) is proportional to the voltage. Therefore, n_{free}/n_{trap} increases with applied electric field resulting in less screening of the E-field by traps and a higher measured μ with increasing applied E-field.

For the 99.30% purity device we can see that the electric field dependence of μ for the DI-SCLC measurements strongly depends on the duty cycle of the measurement. This is because at low duty cycles the device is off for the vast majority of the measurement cycle allowing for the traps to discharge, therefore we can measure the samples mobility without the effect of trapping. At higher duty cycles there is less time for traps to discharge resulting in a stronger dependence of μ on E-field. At a 90% duty cycle we see that the DI-SCLC μ measurements are nearly the same as for AS. In AS the device is constantly driven so in principle a DI-SCLC measurement with 100% duty cycle should give the same result as an AS measurement.

If we examine the 99.90% purity graph we see that the AS measurements and the DI-SCLC measurements for all duty cycles are basically the same. This is because the sample with higher purity does not contain any traps which affect the measurement. This shows that DI-SCLC can be used to confirm that the sample is unaffected by traps. Therefore, we can conclude that making the material more pure will not improve the charge transport.

If one takes look the 1% duty cycle measurements for both purities (replotted in fig.3) we can see that it is indeed the case that a low duty cycle measurement in a sample with traps is equivalent to the measurement in a sample that is not affected by trapping. Therefore, in a sample that is strongly affected by traps it is possible to know how much the charge transport could be improved by eliminating the traps from the sample. In this way the material's potential can be effectively determined prior to investing time and effort to improve the material's performance by increasing the purity.

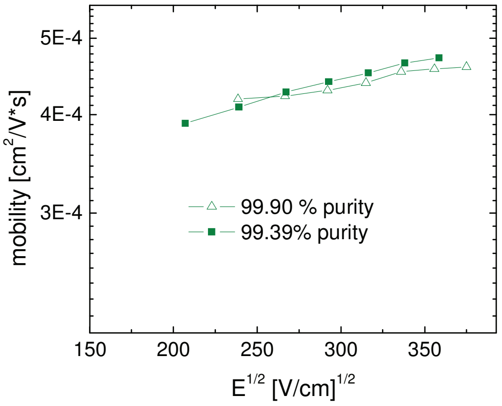

Fig. 3 Comparison of μ vs. $E^{1/2}$ for samples of different purity measured by DI-SCLC with 1% duty cycle.

4. Conclusion

In conclusion DI-SCLC is a powerful method to determine how traps affect the charge transport in charge transport layers. By varying the duty cycle of the measurement pulse it is possible to measure the device without charged traps (low duty cycle) and with charged traps (high duty cycle). Also, the measurements at low duty cycle correspond well to measurements with samples that physically have negligible trapping. Therefore, by using these low duty cycle measurements it is possible to determine how good the charge transport can be once all the traps are removed.

5. References

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