Observing Intrinsic Transport Properties of Single-Crystal Organic Semiconductors using Air-Gap Dielectric FETs

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In organic FETs, charge-carrier traps often form at the interface between a semiconductor organic single crystal and the dielectric layer, reducing the charge-carrier mobility and disrupting observation of the intrinsic-like transport properties of the material; furthermore, these traps inhibit electron injection in most organic semiconductors. Buffer layers, such as PMMA, have been used to reduce the number of electron traps and alleviate this problem with moderate success. A more drastic approach is to eliminate the interface, creating an "Air-gap" transistor, which uses a vacuum or inert gas as the dielectric layer. A patterned PDMS elastomer is used to create the raised surface containing a gap, which is bridged by a single crystal of rubrene (or other organic semiconductors). Work with this type of device has yielded intrinsic hole mobilities as high as 20 $cm^2V^{-1}s^{-1}$ along the b-axis, using four-point probing to separate out the transport effects of the contacts. Further observation of these high-mobility devices would help advance the understanding of the physics of charge transport in these organic semiconductors. Furthermore, with particular electrode materials and configuration, ambipolarity may be achieved, simultaneously injecting both holes and electrons into the channel. Observing ambipolar behavior with such high-mobility devices may also aid in the quest for organic LASERs.

Fabrication of Organic Single Crystal Transistors

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Why Organic Electronics?

Organic Devices
- •LEDs
- •FETs
- •Solar Cells

Advantages
- •Cheaper
- •Flexible
- •Environmentally friendly

Field Effect Transistor (FET)

- •V_D applied across source and drain
- •V_G builds charge between gate and semiconductor
- •Resulting Electric field controls current through the semiconductor (I_D)
- •The relationship between I_D, V_D, and V_G reveals characteristics of the semiconducting material, such as mobility.

Goals

1) Grow rubrene single crystals
2) Fabricate and characterize organic FET devices
   - •Lamination
   - •Air gap
3) Estimate inherent physical properties of rubrene

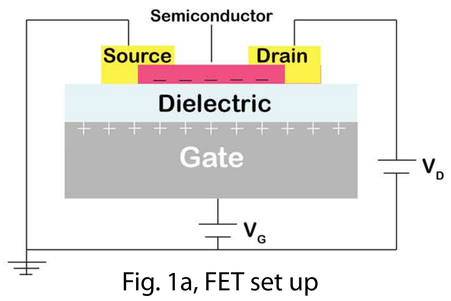

Fig. 1a, FET set up

Why Single Crystals?

- • Eliminates grain boundaries
- • Reduces charge traps
- • Increases mobility
- • Closer to inherent characteristics

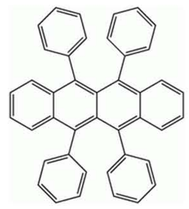

Fig. 1b, Rubrene Crystal

FET Devices

Lamination devices

- • Crystal laminated directly onto dielectric.
- • Thermally deposited Au or hand-applied Ag paste form the electrodes.
- • Charge-carrier traps occur at crystal-dielectric interface.
- • Charge-carrier traps cause lower mobility.

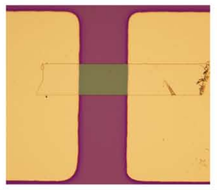

Fig. 1c, Au top contact FET similar to fig 1a.

Air Gap devices

- • Au thermally deposited onto PDMS substrate, simultaneously creating source, drain, and gate.
- • "Air" (usually inert gas or vacuum) is dielectric.
- • No solid interface across the channel,reducing charge-carrier traps.
- • Closer to inherent characteristics of semiconductor.

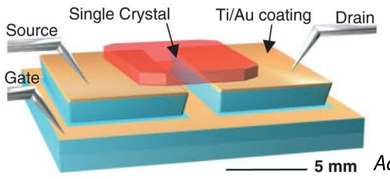

Fig. 1d, Bottom contact air gap FET

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Crystal Growth: Physical Vapor Transport

- •Temperature difference
- •Inert gas flows through tube
- •Powder sublimated into gas
- •Rubrene nucleates, forms crystals

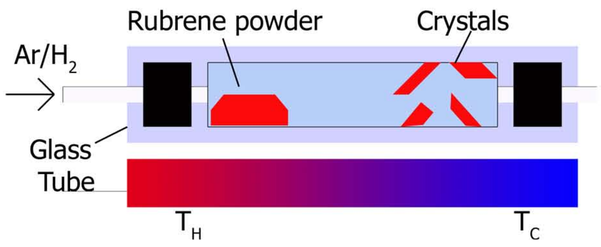


Fig 2a, Diagram of PVT

Construction of a New Furnace

To grow larger and more pure crystals, we needed a new type of furnace.

Old Furnace:

Fig. 2b, Two ovens at T_H and T_C, Insulation gap causes large T drop (see fig. 2d).

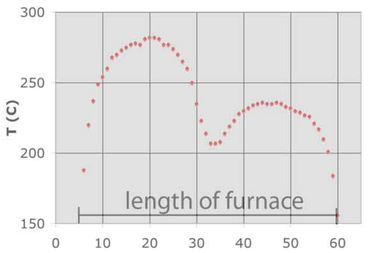


Fig. 2d, Rubrene as well as impurities will deposit at T dip.

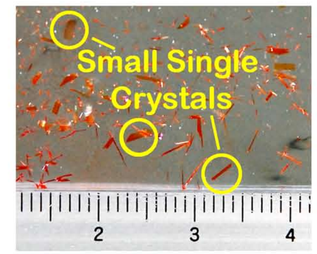


Fig. 2f, smaller crystals grown in old furnace.

New Furnace:

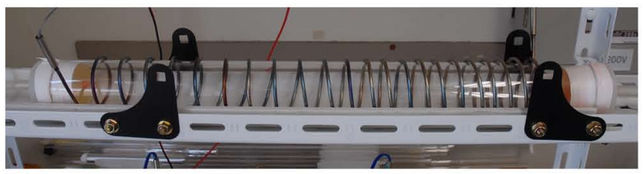


Fig. 2c, Heating filament wrapped around glass tube. Decreasing density of coils causes gradual T drop.

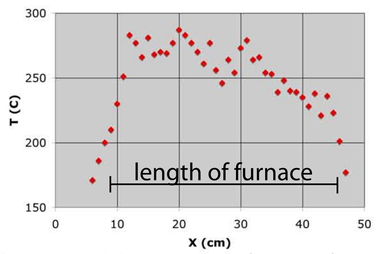


Fig. 2e, Impurities deposit farther from crystal growth, yielding higher-quality crystals.

Fig. 2g, More control allows for larger crystal growth.

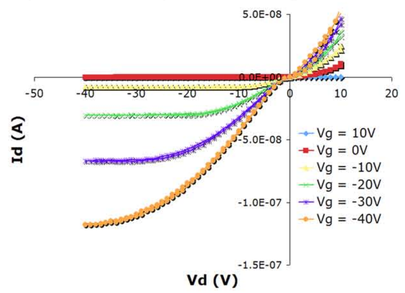
Device Characterization

Output Characteristic Curve
- • V_D vs I_D, varying V_G
- • General behavior
- • Saturation region

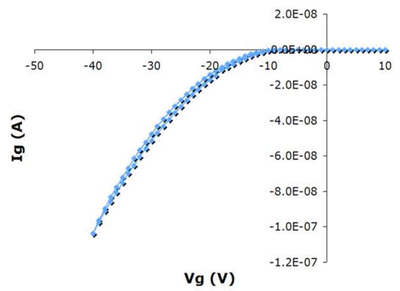
Transport Curve
- • V_G vs I_D
- • Calculate mobility

(above) Fig. 3a, Preparing FET devices
(right) Fig. 3b and c, Typical results for p-channel Output and Transfer curves.

Output Curve of p-channel Ag Paste Device



Transfer Curve of p-channel Ag Paste Device



μ (mobility) = 1.077 $cm^2V^{-1}s^{-1}$

Air Gap Device Difficulties

- • Significant leak current was measured between the source, drain, and gate.
- • Upon SEM imaging (fig. 3g) this was found to be caused by faulty PDMS substrates (fig. 3e).

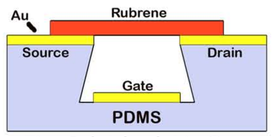


Fig. 3d, Ideal Air Gap

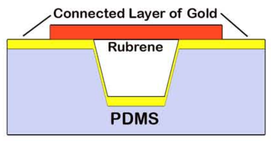


Fig. 3e, Faulty devices used

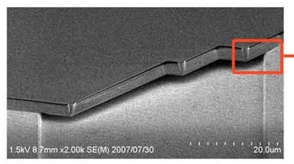


Fig. 3f, SEM image of air gap

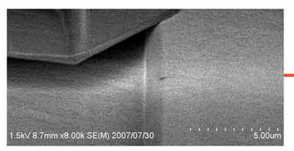


Fig. 3g, Au connecting drain and gate

Conclusions

I was successful in creating a furnace to grow larger and purer crystals for air gap transistors. I was able to fabricate and characterize several different types of lamination devices, achieving relatively high mobilities. The air gap transistors failed, but we were able to find the source of the problem and what we need to do to correct it.

Future Work

- • Continue to optimize growing conditions in the new furnace.
- • Improve structure of PDMS substrates.
- • Create air gap top contact devices.
- • Look for ambipolar behavior with air gap transistors.

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