Carbon contains 6 electrons: \((1s)^2, (2s), (2p_x), (2p_y), (2p_z)\)

\[ \Psi = s + \lambda_x p_x + \lambda_y p_y + \lambda_z p_z \]

Diamond: tetrahedral bond through \(sp^3\) hybrid bonds

Graphite sheet: hexagon bond through \(sp^2\) hybrid bonds
Fig. 4.2 Apparatus for laser evaporation of nanoparticles

Fig. 5.3 Mass spectrum of Carbon clusters. The C\textsubscript{60} and C\textsubscript{70} peaks are evident.
Fig. 5.4 Result of molecular orbital theory for the structure of small clusters

Odd N: linear structure, sp hybridization
Even N: closed structure
Optical extinction

Optical spectrum of light coming from stars in outer space. The peak at 5.6eV (220nm) is due to absorption from C_{60} presented in interstellar dust.

Carbon Star (Red giant)

C_{60} molecules are created in the outer atmosphere of a “red giant”
Atoms are held together by van der Waals forces.
- Contains 12 pentagonal and 20 hexagonal faces.
- The pentagons are needed to produce closed (convex) surfaces, and hexagons lead to a planar surface.
- Dissolves in common solvents like benzene, toluene, hexane
- Readily vaporizes in vacuum around 400 °C
- Low thermal conductivity
- Pure C\textsubscript{60} is an electrical insulator
- C\textsubscript{60} doped with alkali metals shows a range of electrical conductivity:
  - Insulator (K\textsubscript{6} C\textsubscript{60}) to superconductor (K\textsubscript{3} C\textsubscript{60}) < 30 K!

\[
\text{C}_{60}^{3-} \text{ with 3 ionized K}^+ \\
\text{Highly disordered material}
\]

Other superconducting compounds: Rb\textsubscript{3}C\textsubscript{60}, Cs\textsubscript{3}C\textsubscript{60}, Na\textsubscript{3}C\textsubscript{60}
Superconductivity in $K_3C_{60}$

$K_3C_{60}$ : $18K$

$Cs_2RbC_{60}$ : $33K$

$A_3C_{60}$, $A=\text{Alkali}$
Various sizes of fullerenes

Gas-phase production and photoelectron spectroscopy of the smallest fullerene, \( C_{20} \) [Nature, 407, 60 (2000)]
Break junction approach for electrical measurement of a single nano-particle

IV at 1.5K

5nm CdSe

7nm CdSe

Fabrication of metallic electrodes with nanometer separation by electromigration [APL, 75, 301 (1999)]
IV characteristics of a single C\textsubscript{60} transistor at 1.5K

Figure 1 Current–voltage (I–V) curves obtained from a single-C\textsubscript{60} transistor at T= 1.5 K. Five I–V curves taken at different gate voltages (V\textsubscript{g}) are shown. Single-C\textsubscript{60} transistors were prepared by first depositing a dilute toluene solution of C60 onto a pair of connected gold electrodes. A gap of,1 nm was then created using electromigration-induced breaking of the electrodes. Upper inset, a large bias was applied between the electrodes while the current through the connected electrode was monitored (black solid curve). After the initial rapid decrease (solid arrow), the conductance stayed above ,0.05 mS up to ,2.0 V . This behaviour was observed in most single-C\textsubscript{60} transistors, but it was not observed when no C\textsubscript{60} solution was deposited (red dotted curve). The bias voltage was increased until the conductance fell low enough to ensure that the current through the junction was in the tunnelling regime (open arrow). The low bias measurements shown in the main panel were taken after the breaking procedure. Lower inset, an idealized diagram of a single C60-transistor formed by this method.
Two-dimensional differential conductance ($\partial I/\partial V$) plots as a function of the bias voltage ($V$) and the gate voltage ($V_g$). Data were obtained from four different devices prepared from separate fabrication runs. The dark triangular regions correspond to the conductance gap, and the bright lines represent peaks in the differential conductance. a–d, The differential conductance values are represented by the colour scale, which changes from black (0 nS) through pink to white (white representing 30 nS in a, b and c and 5 nS in d). The white arrows mark the point where $\partial I/\partial V$ lines intercept the conductance gap. During the acquisition of data in d, one ‘switch’ where the entire $\partial I/\partial V$ characteristics shift along the $V_g$ axis occurred at $V_g = 1.15$ V. The right portion of the plot d is shifted along the $V_g$ axis to preserve the continuity of the lines.

Charging energy $> 270$meV
Figure 4 Diagram of the centre-of-mass oscillation of C$_{60}$. a, A C$_{60}$ molecule is bound to the gold surface by the van der Waals and electrostatic interaction. The interaction potential is shown schematically alongside. The potential near the equilibrium position can be approximated well by a harmonic potential with a force constant $k$. This harmonic potential gives quantized energy levels with frequency $f \approx \frac{1}{2\pi} (k/ M)^{1/2}$. Here $M$ represents the mass of C$_{60}$ and $h$ the Planck constant. b, When an electron jumps on to C$_{60}^{-}$, the attractive interaction between the additional electron and its image charge on gold pulls the C60 ion closer to the gold surface by the distance $d$. This electrostatic interaction results in the mechanical motion of C60.

$K \approx 70$N/m
$f \approx 1.2$THz
$hf \approx 5$meV
$\delta \approx 4$pm
Chemical vapor deposition: method: methane (CH₄) 1100°C
Catalyst Co or Ni

Laser evaporation
Fabrication of the nanotube devices

Fe catalyst + multiwalled carbon nanotubes grown by CVD

Cr leads
Au leads made by photo-lithography

Cr electrodes made by e-beam lithography
Growth Conditions:

- Substrate: 300nm thermally grown SiO₂
- Catalyst: 9-nm-thermally evaporated iron pads
- Pretreatment: 1mBar hydrogen, ~700 °C, 5 min
- Growth: 1mBar ethylene, ~750 °C, 5 min
TEM 相片：陳貴賢、林麗瓊
Multiwall nanotube consists of capped concentric cylinders separated by ~ 3.5 Å.

- Typically, outer diameter of carbon nanotubes prepared by a carbon arc process ranges between 20 and 200 Å, and inner diameter ranges between 10 and 30 Å. Typical lengths of the arc-grown tubules are about 1 μm, giving rise to an aspect ratio (length-to-diameter ratio) of $10^2$ to $10^3$. 
Forests of multiwalled carbon nanotubes
Fig. 2. (A) Low-magnification SEM image of a long SWNT strand. When the strand is peeled carefully along the length, a thinner SWNT rope is obtained. (B) High-resolution SEM of an array of SWNT ropes peeled from the strand. (C) HRTEM image of a top view of a SWNT rope. For HRTEM observation, we selected a SWNT rope, tore it with tweezers, and affixed it on the HRTEM grid by wetting it with a drop of ethanol or acetone. White arrows indicate the arrangement of the triangle lattice of a large area in a SWNT strand. The inset shows a cross-sectional view of a polycrystalline bundle.