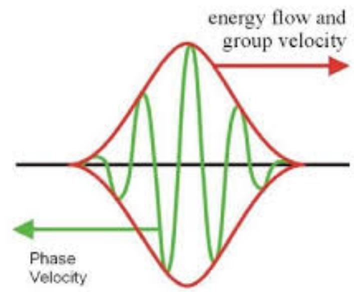
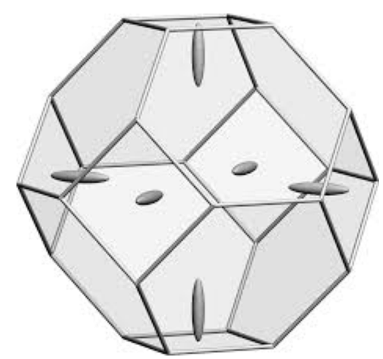
Semiclassical Electron Dynamics:

- Group velocity $\vec{v}_g = \frac{1}{\hbar}\vec{\nabla}_k \varepsilon$



- Effective mass: $\left[M^{-1}\right]_{\alpha\beta} = \frac{1}{\hbar^2}\frac{\partial^2 \varepsilon}{\partial k_\alpha \partial k_\beta}$



Silicon conduction-band pockets (M. Marder)

- Lorentz force equation: $\hbar\dot{\vec{k}} = -e\left[\vec{E} + \frac{1}{\hbar c}\vec{\nabla}_k \varepsilon \times \vec{B}\right]$

Progression to *adjacent states* in *same band.*

  - correct for sufficiently small fields.
  - electric transport properties; also Bloch oscillations (perfect conductor); magnetic quantization effects.

Semiclassical Electron Dynamics

- Lorentz force equation:

$$\hbar\dot{\vec{k}} = -e\left[\vec{E} + \frac{1}{\hbar c}\vec{\nabla}_k \varepsilon \times \vec{B}\right]$$

  - Requires fields sufficiently small for wavepacket to remain within single band.
  - *E* fields: normally difficult to exceed this criterion (Zener breakdown); *B* fields: "magnetic breakdown" sometimes important (several-T fields)

- One consequence: Bloch Oscillations; "no electrical conductivity in perfect crystal"

Bloch oscillations & Transport

- "Paradox": scattering required for charge transport.
- Bloch oscillations seen only in special cases (superlattices, also cooled-atom lattices); need period < τ.

$$\hbar\dot{\vec{k}} = -e\vec{E} \qquad \vec{v}_g(\vec{k}) = \frac{1}{\hbar}\vec{\nabla}_k \varepsilon(\vec{k}) \Rightarrow \vec{r}(t) = \int \vec{v}(\vec{k}(t))dt$$

- Zener tunneling: beyond semi-classical, carriers jump bands. (Extreme quantized: Wannier-Stark ladder in strong E field.)

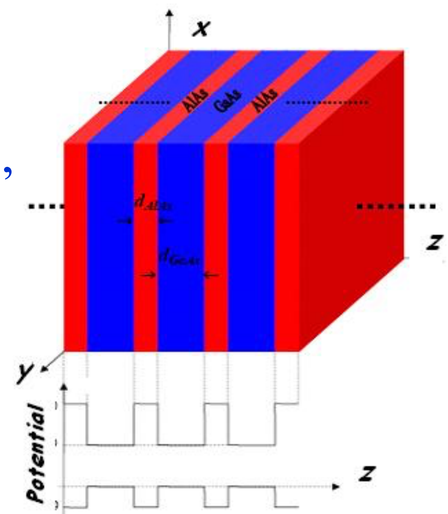
Magnetic cases: Magnetic breakdown;

Shubnikov-de Haas oscillations.

- Esaki idea: superlattice oscillator

Based on Bloch oscillations

"bandgap engineering"



Transport in metals:

Electrical conductivity: typically small "displacement" of FS showed before:

$$k_F = \sqrt[3]{3\pi^2 n} \Rightarrow \varepsilon_F = \hbar^2 k_F^{\,2} / 2m = \hbar^2 (3\pi^2 n)^{2/3} / 2m$$

$$g(\varepsilon_F) = \frac{\sqrt{2}}{\pi^2}\left(\frac{m}{\hbar^2}\right)^{3/2}\sqrt{\varepsilon_F} = \frac{m\left(3\pi^2 n\right)^{1/3}}{\hbar^2\pi^2}$$

Ellipsoidal pocket: replace by $(m_1 m_2 m_3)^{1/2}$

Result for spherical FS :

$$\sigma = \frac{ne^2\tau}{m} = \frac{2}{3} g(\varepsilon_F)\varepsilon_F \frac{e^2\tau}{m} = \frac{g(\varepsilon_F) v_F^2 e^2 \tau}{3}$$

Effective mass

Holes and "Hole bands"

- Hole band as "inverted band structure".

$$\vec{k} \to -\vec{k} \qquad \varepsilon \to -\varepsilon$$

$$-e \to +e \qquad m^* \to -m^*$$

$$\hbar\dot{\vec{k}} = e\left[\vec{E} + \frac{1}{\hbar c}\vec{\nabla}_k \varepsilon \times \vec{B}\right]$$

- Response of positive-charge holes <u>equivalent</u> to response of all the remaining filled electron states; Lorentz force and mass are *reversed*.
- Normally useful only for small pockets, e.g. nearly-full bands.