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Second-Harmonic Generation Induced by Electric Currents in GaAs

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-Presenter: Woongmo Sung-

Current induced Second order susceptibility

When voltage (DC electric field) is applied, there's asymmetric distribution of electrons in CB.

➡ **DC current**

$$\hat{\rho}_{\mathbf{k}} = \begin{vmatrix} \rho_{vv,\mathbf{k}} & \rho_{vc,\mathbf{k}} \\ \rho_{cv,\mathbf{k}} & \rho_{cc,\mathbf{k}} \end{vmatrix} \qquad (4)$$

$$\hat{H}_{\mathbf{k}} = \hat{H}_{0\mathbf{k}} - \frac{e}{m_0}\hat{\mathbf{p}}\cdot\mathbf{A} \qquad \hbar\omega_{0,\mathbf{k}} = E_g + \hbar^2 k^2/2\mu$$

$$= \begin{vmatrix} \frac{1}{2}\hbar\omega_{0,\mathbf{k}} + \frac{e}{m_v}\hbar\mathbf{k}\cdot\mathbf{A} & -\frac{e}{m_0}\mathbf{P}_{vc,\mathbf{k}}\cdot\mathbf{A} \\ -\frac{e}{m_0}\mathbf{P}_{cv,\mathbf{k}}\cdot\mathbf{A} & -\frac{1}{2}\hbar\omega_{0,\mathbf{k}} - \frac{e}{m_c}\hbar\mathbf{k}\cdot\mathbf{A} \end{vmatrix} \qquad (5)$$

Equation of motion (time dependent equation)

$$\frac{\partial\hat{\rho}_{\mathbf{k}}}{\partial t} = \frac{i}{\hbar}[\hat{\rho}_{\mathbf{k}}, \hat{H}_{\mathbf{k}}]$$

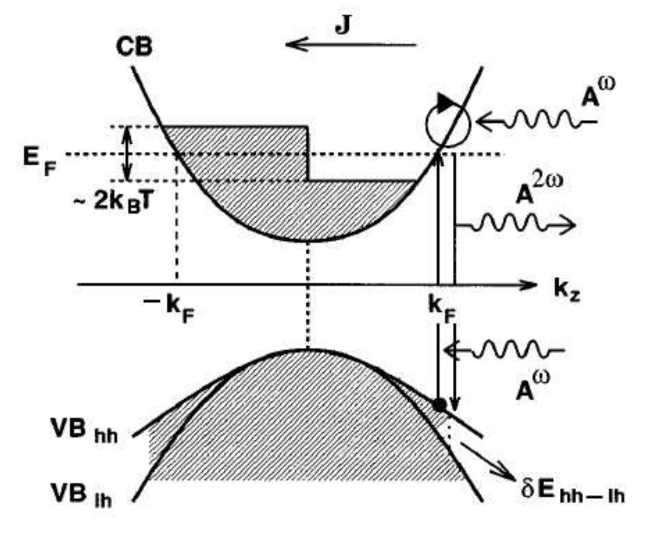


FIG. 1. Band diagram of the states involved in the SHG.

$$\frac{\partial\Delta\rho_{\mathbf{k}}}{\partial t} = 2i\frac{e}{\hbar m_0}\mathbf{A}\cdot(\rho_{cv,\mathbf{k}}\mathbf{P}_{vc,\mathbf{k}} - \rho_{vc,\mathbf{k}}\mathbf{P}_{cv,\mathbf{k}}) - \frac{\Delta\rho_{\mathbf{k}} - \Delta\overline{\rho_{\mathbf{k}}}}{\tau} - \frac{\Delta\rho_{\mathbf{k}} - 1}{\tau_r} \qquad (7)$$

Diagonal term : population in VB and CB.

$$\frac{\partial\rho_{cv,\mathbf{k}}}{\partial t} = -i\omega_{0,\mathbf{k}}\rho_{cv,\mathbf{k}} + i\frac{e}{\mu}\mathbf{k}\cdot\mathbf{A}\rho_{cv,\mathbf{k}} + i\frac{e}{\hbar m_0}\mathbf{P}_{cv,\mathbf{k}}\cdot\mathbf{A}\Delta\rho_{\mathbf{k}} - \frac{\rho_{cv,\mathbf{k}}}{T_2}$$

Off-diagonal term : inter-band transition.

Current induced Second order susceptibility

By solving these equation in terms of second order perturbation.
(* 'Nonlinear Optics , Boyd (second edition) pp.144-165)

$$\rho^{[2\omega]}_{cv,\mathbf{k}} = \frac{e^2}{4\hbar\mu m_0}\left[\frac{(\mathbf{k}\cdot\mathbf{A}^{\omega})(\mathbf{P}_{cv,\mathbf{k}}\cdot\mathbf{A}^{\omega})\Delta\overline{\rho_{\mathbf{k}}}}{(\omega_{0,\mathbf{k}}-2\omega-iT_2^{-1})(\omega_{0,\mathbf{k}}-\omega-iT_2^{-1})}e^{-2i\omega t} + \frac{(\mathbf{k}\cdot\mathbf{A}^{\omega})(\mathbf{P}_{cv,\mathbf{k}}\cdot\mathbf{A}^{\omega})\Delta\overline{\rho_{\mathbf{k}}}}{(\omega_{0,\mathbf{k}}+2\omega-iT_2^{-1})(\omega_{0,\mathbf{k}}+\omega-iT_2^{-1})}e^{2i\omega t}\right] \quad (9)$$

and

$$\Delta\rho^{[2\omega]}_{\mathbf{k}} = -\frac{e^2}{2\hbar^2 m_0^2} \times \frac{(\mathbf{P}_{cv,\mathbf{k}}\cdot\mathbf{A}^{\omega})(\mathbf{P}_{vc,\mathbf{k}}\cdot\mathbf{A}^{\omega})\Delta\overline{\rho_{\mathbf{k}}}}{(\omega_{0,\mathbf{k}}-\omega-iT_2^{-1})(\omega_{0,\mathbf{k}}+\omega-iT_2^{-1})}e^{-2i\omega t} + \text{c.c.} \quad (10)$$

$$\chi^{(2)}_{\mathbf{J}}(2\omega;\omega,\omega) = \frac{e^3}{4\epsilon_0 m_0^2\mu\omega^4(k_B T + i\hbar T_2^{-1})} \times \sum_{\mathbf{k}} \mathbf{P}_{vc,\mathbf{k}}(\mathbf{k}\cdot\hat{\mathbf{e}})(\mathbf{P}_{cv,\mathbf{k}}\cdot\hat{\mathbf{e}})f(\mathbf{k}) \quad (12)$$

Current density

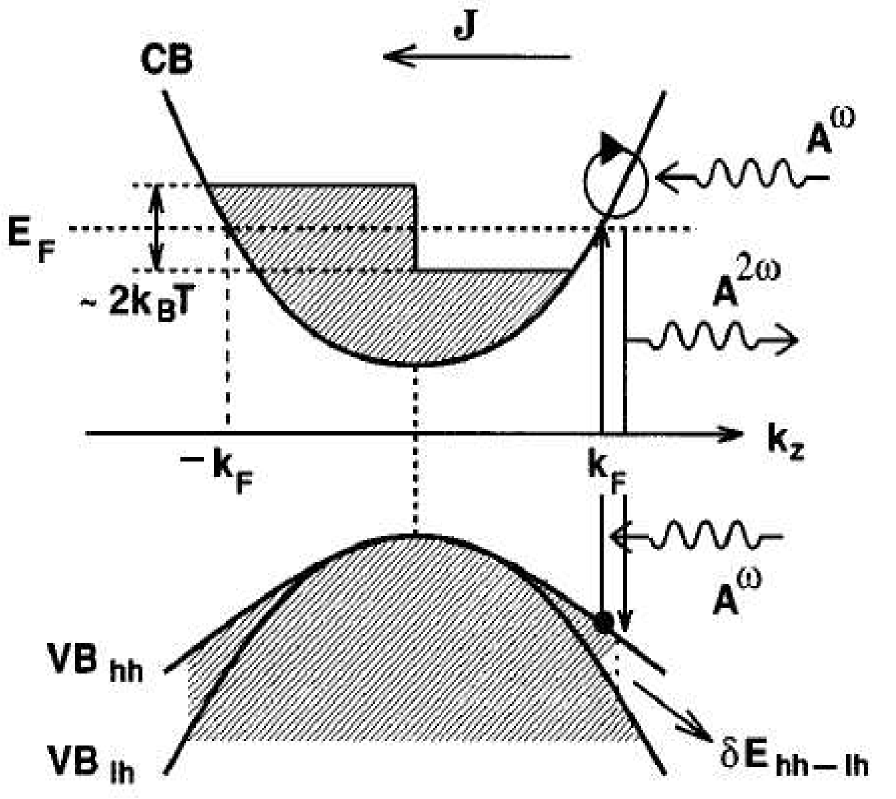
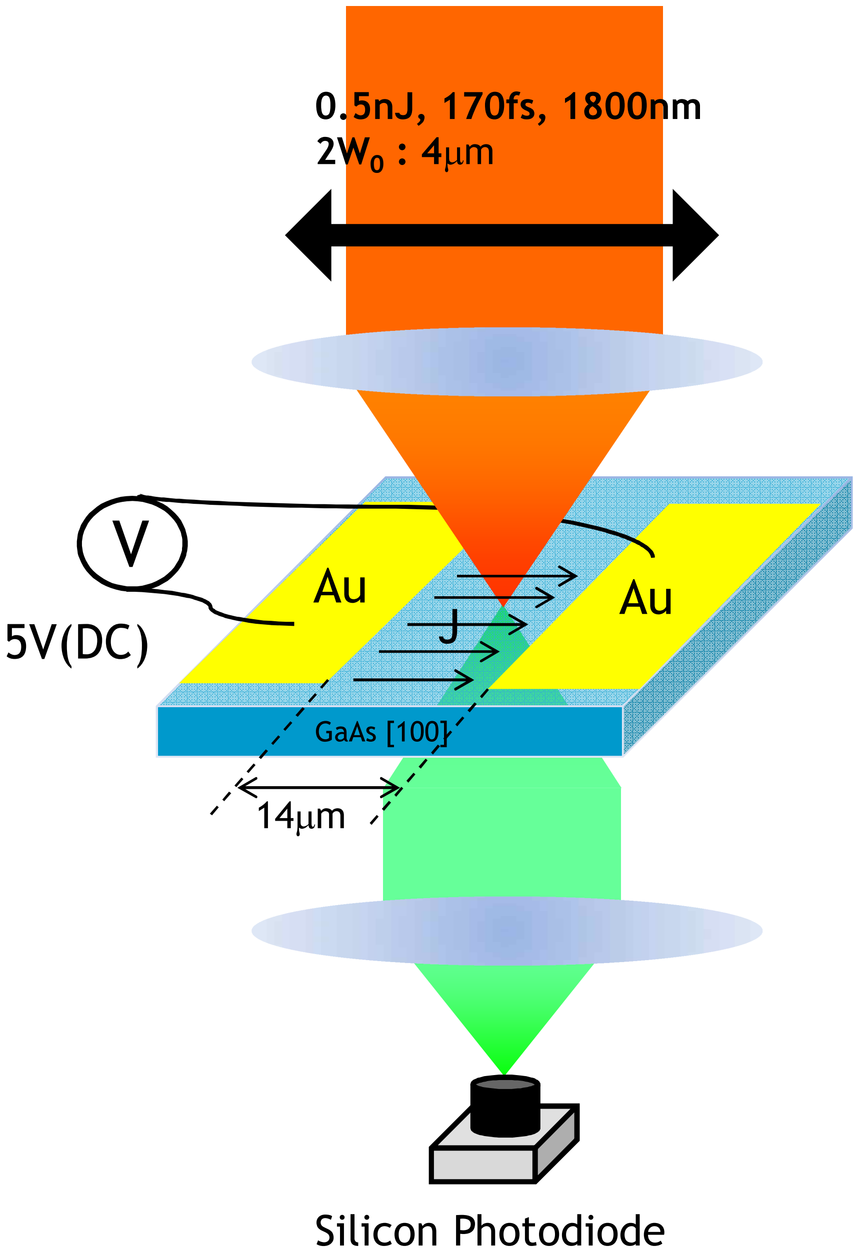
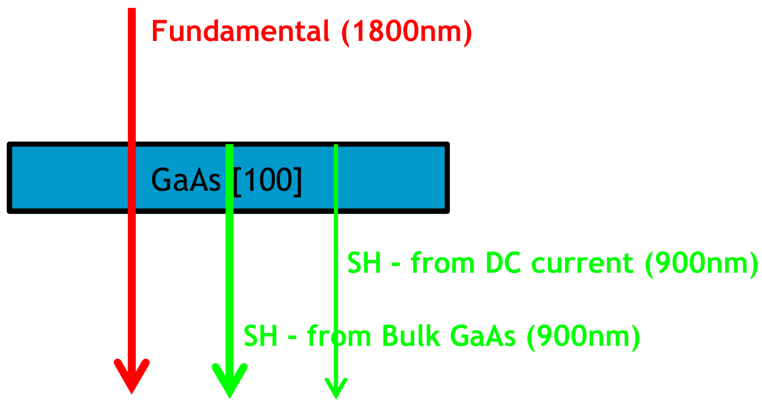


FIG. 1. Band diagram of the states involved in the the SHG.

Experimental setup for measuring current induced SHG



$$\chi_J^{(2)} = \mathcal{P}_{2\omega}^{*}/\varepsilon_0 \mathcal{E}_\omega^2 = \frac{d_{cv}^2}{20\varepsilon_0 \hbar \omega^2 \Delta E_k} J.$$



$$I_{2w} = (E_J + E_{LO})^2$$
$$\sim |E_{LO}|^2 + 2E_{LO}E_J$$
$$= |E_{LO}|^2 + \Delta P$$

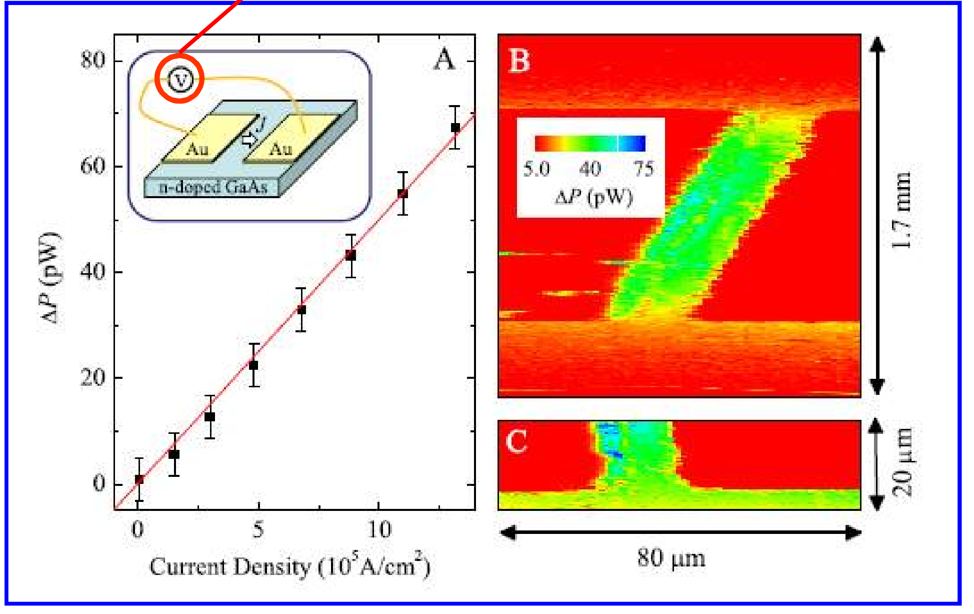
Au electrode (1*2mm^2)

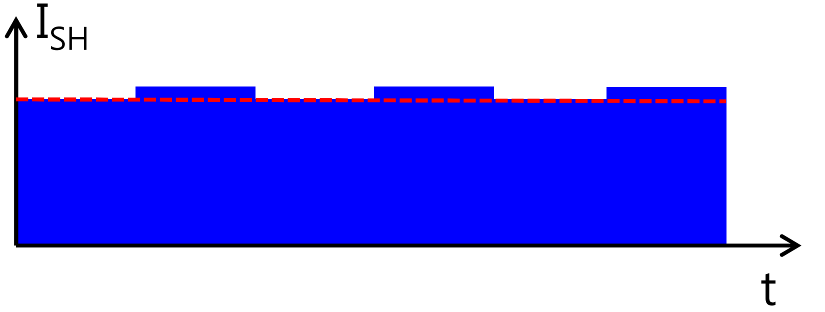
n-type doped GaAs (0.5mm thickness, carrier concentration: $10^{18}/cm^3$)

J = $10^6 A/cm^2$

Current induced SHG

Voltage is modulated with 10Hz square wave for lock-in detection

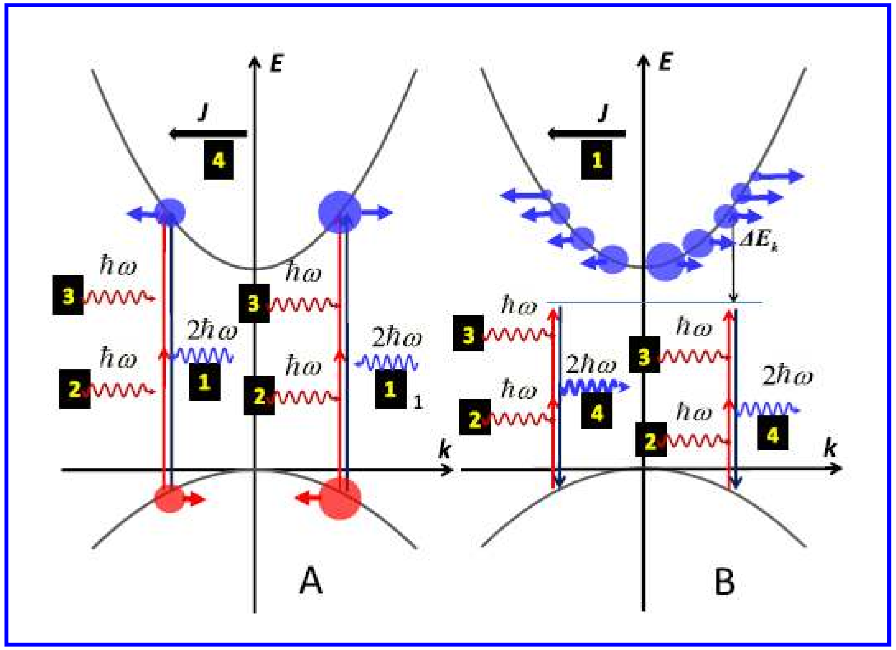


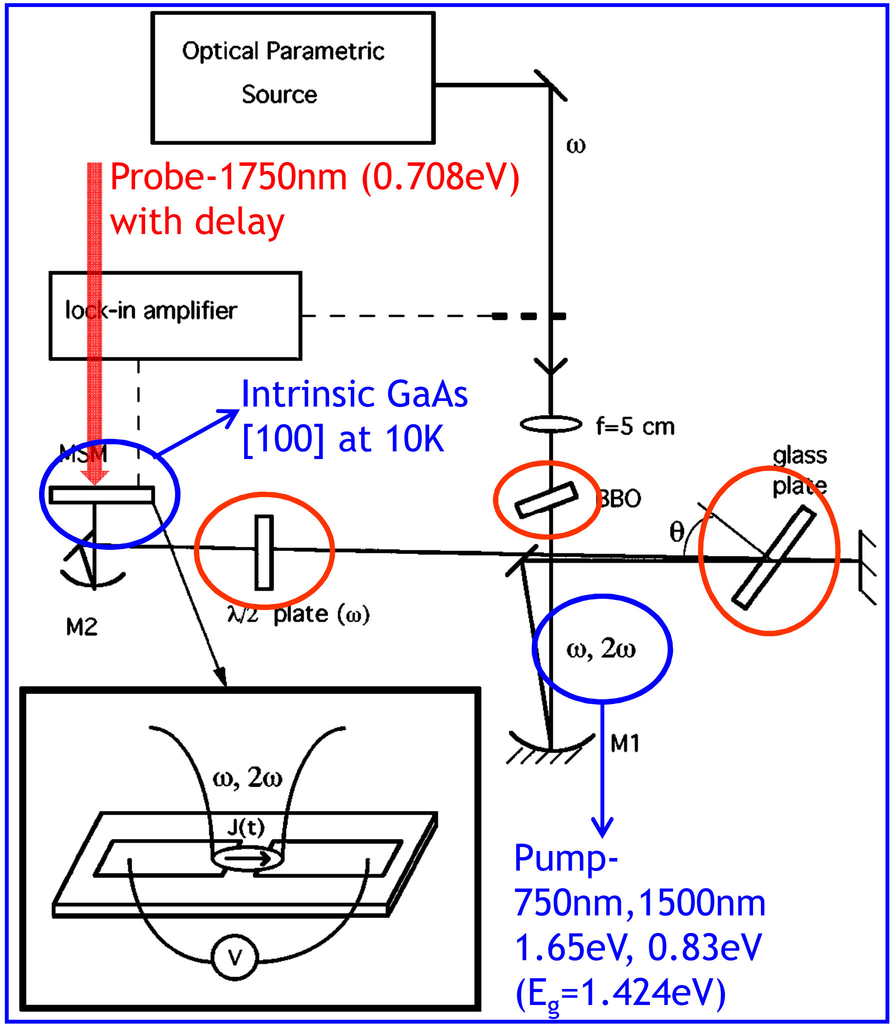


➡ **Transmitted SH intensity (interference) was enhanced between two electrode.**

➡ **SH intensity** $\propto$ *current density* .

Coherent current injection by ultrafast laser pulse



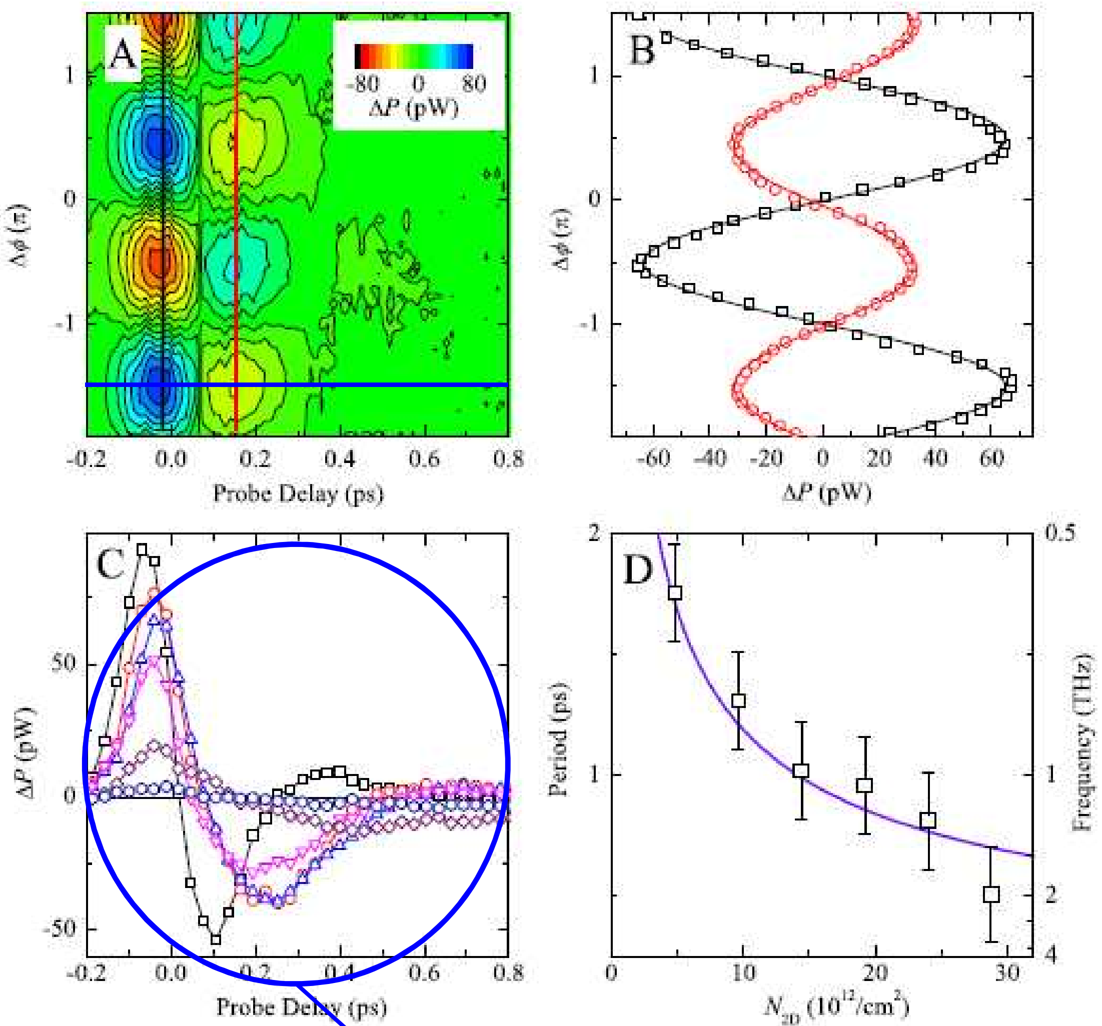


$$\dot{\mathbf{J}}_{e,h} = \hat{\eta}_{e,h} : \mathbf{E}^{\omega}\mathbf{E}^{\omega}\mathbf{E}^{-2\omega} + \text{c.c.} - \mathbf{J}_{e,h}/\tau_{e,h}\,, \qquad (1)$$

$$\dot{J} = 2|\eta_{xxxx}|\,(E_x^{\omega})^2 E_x^{2\omega} \sin(2\phi_{\omega} - \phi_{2\omega}) - \frac{J}{\tau}\,, \qquad (2)$$

➡ **Current generated by w, 2w laser pulse is sensitive to their relative phase.**

SHG from transient current



With varying carrier density

(B)- in fixed delay, SH intensity is proportional to sin(Δϕ)

(C)- Δϕ=π/2, SH intensity shows damped oscillation (Plasma oscillation)

(d)- Oscillation frequency depends on pump intensity

$$\omega_p = \sqrt{\frac{Ne^2}{m^* \varepsilon_o}}$$

Summary

1) It was able to observe SHG from DC current.

2) Probing by ultrashort pulse, transient current could be monitored within 0.1ps.

3)Transition current amplitude and its plasma frequency were controlled by optical pumping