Modeling of electronic dynamics in swift heavy ion irradiated semiconductors

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Motivation

- The modern particle physics requires the use of extremely large and costly composite detectors. The new generation of high energy experiments at colliders will use semiconductor (silicon) tracking detectors in a heavier way than in the past.
- One of the scientific pillars of FAIR is nuclear-structure physics with radioactive ion beams.
- The semiconductor (silicon) instrumented trackers detectors should be fully operational for at least *10 years*
- Detector diagnostic and repair comprises a very expensive and labor-consuming procedure.
- At the microscopic level the radiation damage suffered by the detectors can be divided in two different classes: effects which are due to surface damage and those which are due to **bulk damage**.

 The study of interaction of swift heavy ions with semiconductor single crystals is very important both for the fundamental investigations of radiation effects in condensed matter and for the creation of ion tracks in semiconductor materials – provides detector reliability and hardness insurance.

 To achieve microscopic understanding of the fast ion irradiation of materials used for detectors we restrict ourselves to describing the damage produced in GaAs semiconductor when irradiated with swift heavy ions (coming from a given experimental radiation environment) by

 utilizing a theory developed for GaAs material irradiated with femotosecond laser pulse. •We consider a bulk GaAs semiconductor doped with electron concentration to form a 3D electron gas.

•We separate the dynamics of a many-electron system into a center-of-mass motion plus a relative motion under both dc and infrared fields-

•X.L. Lei and C.S. Ting, J. Phys. C **18**, 77 (1985), D. Huang, T. Apostolova, P. Alsing, D. A. Cardimona, Phys. Rev. B 69, 075214 (2004)

•The relative motion of electrons is studied by using the Boltzmann scattering equation including anisotropic scattering of electrons with phonons and impurities beyond the relaxation-time approximation.

•The coupling of the center-of-mass and relative motions can be seen from the impurity and phonon parts of the relative Hamiltonian •The incident electromagnetic field is found to be coupled only to the center-of-mass motion but not to the relative motion of electrons.

•This generates an oscillating drift velocity in the center-of mass motion, but the time-average value of this drift velocity remains zero.

$$\hat{H}_{CM} = \frac{(\hat{\vec{P}}^{C})^{2}}{2N_{e}m^{*}} + \frac{N_{e}e^{2}A^{2}}{2m^{*}} - \frac{e\vec{A}.\hat{\vec{P}}^{C}}{m^{*}}$$

•The oscillating drift velocity, however, affects the electronphonon and electron-impurity interactions.

•The dynamics of electrons is determined by the relative motion of electrons - scattering of electrons with impurities, phonons, and other electrons. •The effect of an incident optical field is reflected in the impurity- and phonon-assisted photon absorption through modifying the scattering of electrons with impurities and phonons.

•The distribution of electrons is driven away from the thermal equilibrium distribution to a **non-equilibrium** one.

•The electron average kinetic energy (temperature) **increases** with the strength of the incident electromagnetic field, creating hot electrons.

Previously- Boltzmann scattering equation – impurity and phononassisted photon absorption and Coulomb electron scattering for a doped GaAs semiconductor

$$\frac{\partial}{\partial t}n_{\vec{k}}^{e} = W_{k}^{(in)(\alpha)}\left(1 - n_{\vec{k}}^{e}\right) - W_{k}^{(in)(\alpha)}n_{\vec{k}}^{e} \qquad \alpha = (im), (ph), (c)$$

$$W_{k}^{(in)(ph)} = \frac{2\pi}{\hbar} \sum_{\bar{q}\lambda,M} \left| C_{\bar{q}\lambda} \right|^{2} J_{|M|}^{2} \left(e \left| \vec{q} \cdot \vec{E} \left(t \right) \right| / \sqrt{2} m^{*} \Omega_{L}^{2} \right)^{2} \times \left[n_{\vec{k}-\vec{q}} N_{\bar{q}\lambda}^{ph} \delta \left(E_{\vec{k}} - E_{\vec{k}-\vec{q}} - \hbar \omega_{\bar{q}\lambda} - M \hbar \Omega_{L} \right) + n_{\vec{k}+\vec{q}} \left(N_{\bar{q}\lambda}^{ph} + 1 \right) \delta \left(E_{\vec{k}} - E_{\vec{k}+\vec{q}} + \hbar \omega_{\bar{q}\lambda} + (M \hbar \Omega_{L}) \right) \right]$$

$$\left|C_{q\lambda}\right|^{2} = \left(\frac{\hbar\omega_{LO}}{2V}\right) \left(\frac{1}{\varepsilon_{\infty}} - \frac{1}{\varepsilon_{0}}\right) \frac{e^{2}}{\varepsilon_{0}\left(q^{2} + Q_{s}^{2}\right)}$$

$$W_{k}^{(in)(im)} = n_{I} \sum_{\vec{q},M} \left| U^{(im)}(q) \right|^{2} J_{|M|}^{2} \left(e \left| \vec{q}.\vec{E}(t) \right| / \sqrt{2} m^{\ell} \Omega_{L}^{2} \right)^{2} \times \left[n_{\vec{k}-\vec{q}} \delta \left(E_{\vec{k}} - E_{\vec{k}-\vec{q}} - M\hbar \Omega_{L} \right) + n_{\vec{k}+\vec{q}} \delta \left(E_{\vec{k}} - E_{\vec{k}+\vec{q}} + M\hbar \Omega_{L} \right) \right]$$

$$\left| U^{(im)}(q) \right| = \frac{Ze^2}{\varepsilon_0 \varepsilon_r \left(q^2 + Q_s^2 \right)}$$

$$W_{k}^{(in)(c)} = \frac{2\pi}{\hbar} \sum_{\vec{k}',\vec{q}} \left| V^{(c)}(q) \right|^{2} \left(1 - n_{\vec{k}'} \right) n_{\vec{k}-\vec{q}} n_{\vec{k}'+\vec{q}} \times \delta\left(E_{\vec{k}} - E_{\vec{k}'} - E_{\vec{k}-\vec{q}} - E_{\vec{k}'+\vec{q}} \right)$$

$$\left|V^{(c)}(q)\right| = \frac{e^2}{\varepsilon_0 \varepsilon_r \left(q^2 + Q_s^2\right)V}$$





•The projectile has reached its equilibrium charge state - there will be only minor fluctuations of its internal state

• It will move with constant velocity along a straight-line trajectory until deep inside the solid.

•Thus, the projectile ion acts as a well defined and virtually instantaneous source of strongly localized electronic excitation.

G. Schiwietz et al. / Nucl. Instr. and Meth. in Phys. Res. B 225 (2004) 4–26

Parallelism

From the fundamental point of view ion damage presents similarities with femtosecond-laser pulse damage.

- Deposition of localized high energy densities in solid matter due to very dense electronic excitation by means of either photons or energetic ions leading to the formation of dense electron-hole plasma.
- The interaction occurs roughly in the same time scale and creates highly-localized material excitations $\tau \approx 100 fs 1 ps$

$$\tau = b / v_p$$
 – collision time

Electron dynamics in ion-semiconductor interaction

In terms of three-dimensional Cartesian coordinates, we define the reaction to occur in the x-y plane with the beam directed along \vec{e}_x and the impact parameter b along \vec{e}_y defining the straight-line trajectory to be



We establish a Boltzmann scattering equation for the relative scattering motion of electrons interacting with a swift heavy ion by

•considering Coulomb interaction between the ion projectile and the electron system

•including both the impurity- and phonon-assisted photon absorption processes as well as the Coulomb scattering between two electrons.

•We study the dynamics of electrons by calculating the average kinetic energy as a function of impact parameter and charge of the ion.

Use the Hamiltonian

$$H = \frac{1}{2m^{*}} \sum_{i} \hat{\vec{p}}_{i}^{2} + \sum_{i < j} \frac{e^{2}}{4\pi\varepsilon_{0}\varepsilon_{r} |\vec{r}_{i} - \vec{r}_{j}|} - \sum_{i} \frac{Ze^{2}}{4\pi\varepsilon_{0}\varepsilon_{r} |\vec{r}_{p} - \vec{r}_{i}|} + \sum_{i,a} U^{imp}(\vec{r}_{i} - \vec{R}_{imp})$$

$$\hat{\vec{P}}^{C} = \sum_{i=1}^{N_{e}} \hat{\vec{p}}_{i} \qquad \vec{R}^{C} = \frac{1}{N_{e}} \sum_{i=1}^{N_{e}} \hat{\vec{r}}_{i}, \qquad \hat{\vec{p}}_{i}' = \hat{\vec{p}}_{i} - \frac{1}{N_{e}} \hat{\vec{P}}^{C} \qquad \qquad \vec{r}_{i}' = \vec{r}_{i} - \vec{R}^{C}$$



$$\begin{aligned} \hat{H}_{rel} &= \sum_{\vec{k},\sigma} \varepsilon_k \hat{a}^{\dagger}_{\vec{k}\sigma} \hat{a}_{\vec{k}\sigma} + \sum_{\vec{q},\lambda} \hbar \omega_{q\lambda} \hat{b}^{\dagger}_{\vec{q}\lambda} \hat{b}_{\vec{q}\lambda} + \frac{1}{2} \sum_{\vec{k},\vec{k}',\sigma,\sigma'} \sum_{\vec{q}} \frac{e^2}{\varepsilon_0 \varepsilon_r q^2 \nu} \hat{a}^{\dagger}_{\vec{k}+\vec{q}\sigma} \hat{a}^{\dagger}_{\vec{k}'-\vec{q}\sigma'} \hat{a}_{\vec{k}\sigma'} \hat{a}_{\vec{k}\sigma'} + \\ &+ \sum_{\vec{k},\sigma} \sum_{\vec{q},\lambda} C_{q\lambda} (\hat{b}_{\vec{q}\lambda} + \hat{b}^{\dagger}_{-\vec{q}\lambda}) e^{i\vec{q}.\vec{R}^c} \hat{a}^{\dagger}_{\vec{k}+\vec{q}\sigma} \hat{a}_{\vec{k}\sigma} - \sum_{\vec{k},\sigma} \sum_{\vec{q}} \frac{Ze^2}{\varepsilon_0 \varepsilon_r q^2 \nu} e^{i\vec{q}.(\vec{R}^c - \vec{r}_p)} \hat{a}^{\dagger}_{\vec{k}+\vec{q}\sigma} \hat{a}_{\vec{k}\sigma} + \dots \end{aligned}$$

Solve the time-dependent Schrodinger equation

$$i\hbar \frac{\partial \psi(\vec{r},t)}{\partial t} = \frac{\vec{p}^2}{2m^*} \psi(\vec{r},t) + V_p(\vec{r},t) \psi(\vec{r},t)$$

$$V_{p}(\vec{r},t) = -\frac{Ze^{2}}{4\pi\varepsilon_{0}|\vec{r}-\vec{r}_{p}(t)|}$$

L.Plagne et. al. Phys. Rev. B 61, (2000), J.C.Wells, et. al. Phys. Rev. B 54, (1996)

$$\vec{r}_p(t) = (v_p t, b, 0)$$

with velocity of projectile $~{\cal V}_p$

$$\psi\left(\vec{r},t\right) = \frac{e^{i\vec{k}\cdot\vec{r}}}{\sqrt{V}}f(t)$$

$$f(t) = f(0)e^{\frac{i}{\hbar}\frac{Ze^2}{4\pi\varepsilon_0 v_p}\ln(t+\sqrt{t^2+a^2})}e^{-\frac{i}{\hbar}\frac{Ze^2}{4\pi\varepsilon_0 v_p}\ln(a)}$$

$$a = \frac{b}{v_p}; c = \frac{Ze^2}{4\pi\varepsilon_0 v_p}$$

$$f(t) = f(0)e^{\frac{i}{\hbar}c\ln(t+\sqrt{t^2+a^2})}e^{-\frac{i}{\hbar}c\ln(a)}$$

$$c\ln(t + \sqrt{t^2 + a^2}) = c\ln a + c\frac{t}{a} - c\frac{t^3}{6a^3} + c\frac{3t^3}{40a^5} - \dots$$

$$c\ln(t + \sqrt{t^2 + a^2}) \approx c\ln a + c\frac{t}{a}$$

Looking closely at the problem parameters for justification of the approx.

The electron annihilation operator in the ion potential is given by:

$$\hat{c}_{\vec{k}}(t) = \hat{a}_{\vec{k}}(t) \exp\left[\frac{i}{\hbar}c\ln\left(t + \sqrt{t^2 + a^2}\right)\right] \exp\left[-\frac{i}{\hbar}c\ln\left(a\right)\right]$$

Boltzmann type scattering equation

$$\frac{\partial}{\partial t}n_{\vec{k}}^{e} = W_{k}^{(in)(\alpha)}\left(1 - n_{\vec{k}}^{e}\right) - W_{k}^{(in)(\alpha)}n_{\vec{k}}^{e} \qquad \alpha = (im), (ph), (c)$$

$$W_{k}^{(in)(ph)} = \frac{2\pi}{\hbar} \sum_{\bar{q}\lambda} \left| C_{\bar{q}\lambda} \right|^{2}$$

$$\times \left[n_{\vec{k}-\vec{q}} N_{\bar{q}\lambda}^{ph} \delta\left(E_{\vec{k}} - E_{\vec{k}-\vec{q}} - \hbar \omega_{\bar{q}\lambda} + Ze^{2}/b4\pi\varepsilon_{0} \right) + n_{\vec{k}+\vec{q}} \left(N_{\bar{q}\lambda}^{ph} + 1 \right) \delta\left(E_{\vec{k}} - E_{\vec{k}+\vec{q}} + \hbar \omega_{\bar{q}\lambda} + Ze^{2}/b4\pi\varepsilon_{0} \right) \right]$$

$$W_{k}^{(in)(im)} = n_{I} \sum_{\bar{q}} \left| U^{(im)}(q) \right|^{2} \times \left[n_{\vec{k}-\vec{q}} \delta\left(E_{\vec{k}} - E_{\vec{k}-\vec{q}} + Ze^{2} / b 4\pi\varepsilon_{0} \right) + n_{\vec{k}+\vec{q}} \delta\left(E_{\vec{k}} - E_{\vec{k}+\vec{q}} + Ze^{2} / b 4\pi\varepsilon_{0} \right) \right]$$

$$W_{k}^{(in)(c)} = \frac{2\pi}{\hbar} \sum_{\vec{k}', \vec{q}} \left| V^{(c)}(q) \right|^{2} \left(1 - n_{\vec{k}'} \right) n_{\vec{k} - \vec{q}} n_{\vec{k}' + \vec{q}} \times \delta \left(E_{\vec{k}} - E_{\vec{k}'} - E_{\vec{k} - \vec{q}} - E_{\vec{k}' + \vec{q}} \right)$$

Numerical results

TABLE I. Parameters of the ion irradiations.

Ion	Energy (MeV/ <i>u</i>)	Range (µm)	$(dE/dx)_i$ (keV/nm)	Mean (dE/dx) (keV/nm)
⁵⁸ Ni	11.4	96	5.4	6.9
⁶⁸ Zn	11.4	96	6.0	8.1
⁸² Se	11.4	104	7.4	9.0
⁸⁴ Kr	11.4	98	8.0	9.8
¹³⁰ Xe	11.4	91	14.3	16.3
¹⁹⁷ Au	11.4	96	24.0	23.4
	5.4	49	27.0	21.7
²⁰⁸ Pb	11.4	96	24.9	24.7
	5.4	49	27.9	22.9
	4.0	38	27.9	21.9
²⁰⁹ Bi	11.4	95	25.4	25.1
	10.9	91	25.7	25.0
²³⁸ U	11.4	100	28.8	27.1

K. Schwartz, C. Trautmann, T. Steckenreiter, O. Geiß, and M. Krämer, Phys. Rev. B 58, 11232–11240 (1998)

hydrogen					1070		1984	1	070			10.00	1.0	698	87.57.5		010	helium
																		2
H																		He
1.0079																		4.0026
lithium 3	beryllium A												boron 5	carbon 6	nitrogen 7	oxygen 8	fluorine Q	neon 10
ľ.	De												Ď	Č	Ň	Ô	Ē	No
	ве												D		IN	U		ne
6.941	9.0122												10.811	12.011	14.007	15.999	18.998	20.180
11	magnesium 12												auminium 13	14	phosphorus 15	16	chiorine 17	argon 18
Na	Mg												AI	Si	Ρ	S	CI	Ar
22.990	24.305												26.982	28.086	30.974	32.065	35.453	39.948
potassium 10	calcium 20		scandium 21	titanium 22	vanadium 23	chromium 24	manganese 25	iron 26	cobalt 27	nickel 28	copper 20	zinc 30	gallium 21	germanium 32	arsenic 33	selenium 3/1	bromine 35	krypton 36
15	20		21	~~	25	24	25	20	21	20	25	50	51	52	55	54	55	50
	0		0 -			0	N /1		0		0	7	0 -	0 -	A	0	D	
K	Ca		Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
K 39.098	Ca 40.078		Sc 44.956	Ti 47.867	V 50.942	Cr 51.996	Mn 54.938	Fe 55.845	Co 58.933	Ni 58.693	Cu 63.546	Zn 65.39	Ga 69.723	Ge 72.61	As 74.922	Se 78.96	Br 79.904	Kr 83.80
39.098 rubidium	Ca 40.078 strontium		44.956 yttrium	47.867 zirconium	50.942 niobium	51.996 molybdenum	54.938 technetium	55.845	58.933 rhodium	58.693 palladium	63.546 silver	Zn 65.39 cadmium	Ga 69.723 Indium	Ge 72.61 tin 50	As 74.922 antimony	Se 78.96 tellurium	Br 79.904 Iodine	83.80 xenon
8 39.098 rubidium 37	Ca 40.078 strontium 38		Sc 44.956 yttrium 39	47.867 zirconium 40	50.942 niobium 41	51.996 molybdenum 42	Mn 54.938 technetium 43	Fe 55.845 ruthenium 44	Co 58.933 rhodium 45	Ni 58.693 palladium 46	63.546 silver 47	Zn 65,39 cadmium 48	Ga 69.723 indium 49	Ge 72.61 tin 50	As 74.922 antimony 51	Se 78.96 tellurium 52	8r 79.904 iodine 53	Kr 83.80 xenon 54
8 39.098 rubidium 37 Rb	Ca 40.078 strontium 38 Sr		Sc 44.956 yttrium 39 Y	Ti 47.867 zirconium 40 Zr	V 50.942 niobium 41 Nb	Cr 51.996 molybdenum 42 Mo	Mn 54.938 technetium 43 TC	Fe 55.845 ruthenium 44 Ru	Co 58.933 rhodium 45 Rh	Ni 58.693 palladium 46 Pd	Cu 63.546 silver 47 Ag	Zn 65.39 cadmium 48 Cd	Ga 69.723 indium 49 In	Ge 72.61 tin 50 Sn	As 74.922 antimony 51 Sb	Se 78.96 tellurium 52 Te	Br 79.904 iodine 53 I	Кг ^{83.80} хепоп 54 Хе
8 39.098 rubidium 37 Rb 85.468	Ca 40.078 strontium 38 Sr 87.62		Sc 44.956 yttrium 39 Y 88.906	47.867 zirconium 40 Zr 91.224	V 50.942 niobium 41 Nb 92.906	Cr 51.996 molybdenum 42 Mo 95.94	Mn 54.938 technetium 43 Tc [98]	Fe 55.845 ruthenium 44 Ru 101.07	Co 58.933 rhodium 45 Rh 102.91	Ni 58,693 palladium 46 Pd 106,42	Cu 63.546 silver 47 Ag 107.87	Zn 65.39 cadmium 48 Cd 112.41	Ga 69,723 indium 49 In 114,82	Ge 72.61 tin 50 Sn 118.71	As 74.922 antimony 51 Sb 121.76	Se 78.96 tellurium 52 Te 127.60	Br 79.904 iodine 53 I 126.90	Kr 83.80 xenon 54 Xe 131.29
K 39.098 rubidium 37 Rb 85.468 caesium	Ca 40.078 strontium 38 Sr 87.62 barium 56	57 70	SC 44.956 yttrium 39 Y 88.906 lutetium 71	Ti 47.867 zirconium 40 Zr 91.224 hafnium 72	V 50.942 niobium 41 Nb 92.906 tantalum	Cr 51.996 molybdenum 42 Mo 95.94 tungsten 74	Mn 54.938 technetium 43 TC [98] rhenium 75	Fe 55.845 ruthenium 44 Ru 101.07 osmium 76	Co 58.933 rhodium 45 Rh 102.91 iridium 77	Ni 58.693 palladium 46 Pd 106.42 platinum 78	63.546 silver 47 Ag 107.87 gold	Zn 65.39 cadmium 48 Cd 112.41 mercury	Ga 69.723 Indium 49 In 114.82 thallium	Ge 72.61 tin 50 Sn 118.71 lead	As 74.922 antimony 51 Sb 121.76 bismuth 92	Se 78.96 tellurium 52 Te 127.60 polonium	Br 79.904 Iodine 53 I 126.90 astatine	Kr 83.80 xenon 54 Xe 131.29 radon
K 39,098 rubidium 37 Rb 85,468 caesium 55	Ca 40.078 strontium 38 Sr 87.62 barlum 56	57-70	Sc 44.956 yttrium 39 Y 88.906 lutetium 71	Ti 47.867 zirconium 40 Zr 91.224 hafnium 72	V 50.942 niobium 41 Nb 92.906 tantalum 73 73	51.996 molybdenum 42 Mo 95.94 tungsten 74	Mn 54.938 Itechnetium 43 Tc [98] rhenium 75	55.845 ruthenium 44 Ruu 101.07 osmium 76	Co 58.933 rhodium 45 Rh 102.91 iridium 77	Ni 58,693 palladium 46 Pd 106,42 platinum 78	63.546 sliver 47 Ag 107.87 gold 79	Zn 65.39 cadmium 48 Cd 112.41 mercury 80	Ga <u>69,723</u> indium 49 In <u>114.82</u> thallium 81	Ge 72.61 tin 50 Sn 118.71 lead 82	As 74.922 antimony 51 Sb 121.76 bismuth 83	Se 78.96 tellurium 52 Te 127.60 polonium 84	79.904 iodine 53 1 126.90 astatine 85	Kr 83.80 xenon 54 Xe 131.29 radon 86
839.098 rubidium 37 Rbb 85.468 caesium 55 Cs	Ca 40.078 strontium 38 Sr 87.62 barium 56 Ba	57-70 X	Sc 44.956 yttrium 39 Y 88.906 lutetium 71 Lu	Ti 47.867 zirconium 40 Zr 91.224 hafnium 72 Hf	V 50.942 niobium 41 Nb 92.906 tantalum 73 Ta	Cr ^{51.996} molybdenum 42 Moo 95.94 tungsten 74 W	Mn 54.938 technetium 43 Tcc 989 rhenium 75 Re	Fe 55.845 ruthenlum 44 Ru 101.07 osmium 76 OS	Co 58.933 rhodium 45 Rh 102.91 iridium 77 Ir	Ni 58,693 palladium 46 Pd 106,42 platinum 78 Pt	Cu 63.546 silver 47 Agg 107.87 gold 79 Au	Zn 65.39 cadmium 48 Cd 112.41 mercury 80 Hg	Ga 69.723 indium 49 In 114.82 thallium 81 TI	Ge 72.61 tin 50 Sn 118.71 lead 82 Pb	As antimony 51 Sb 121.76 bismuth 83 Bi	Se 78.96 tellurium 52 Te 127.60 polonium 84 PO	Br 79.904 iodine 53 l 126.90 astatine 85 At	Kr 83.80 xenon 54 Xe 131.29 radon 86 Rn
K 39.098 rubidium 37 Rbb 85.468 caesium 55 CS 132.91	Ca 40.078 strontlum 38 Sr 87.62 barlum 56 Ba 137.33	57-70 ★	Sc 44.956 yttrium 39 Y 88.906 lutetium 71 Lu 174.97	Ti 47.867 zirconium 40 Zr 91.224 hafnium 72 Hf 178.49	V 50.942 niobium 41 Nbb 92.906 tantalum 73 Ta 180.95	Cr 51.996 molybdenum 42 MO 95.94 tungsten 74 W 183.84	Mn 54.938 technetium 43 Tcc 198 rhenium 75 Re 186.21	Fe 55.845 ruthenlum 44 Ru 101.07 osmium 76 Os 190.23	Co 58.933 rhodium 45 Rh 102.91 iridium 77 Ir 192.22	Ni 58,693 palladium 46 Pd 106,42 platinum 78 Pt 195.08	Cu 63.546 silver 47 Ag 107.87 gold 79 Au 196.97	Zn 65.39 cadmium 48 Cd 112.41 mercury 80 Hg 200.59	Ga 69.723 Indium 49 In 114.82 thallium 81 TI 204.38	Ge 72.61 tin 50 Sn 118.71 lead 82 Pb 207.2	As 74.922 antimony 51 Sb 121.76 bismuth 83 Bi 208.98	Se 78.96 tellurium 52 Te 127.60 polonium 84 PO [209]	Br 79.904 iodine 53 I 126.90 astatine 85 At [210]	Kr 83.80 xenon 54 Xe 131.29 radon 86 Rn [222]
K 39.098 rubidium 37 Rbb 85.468 caesium 55 Cs 132.91 francium 87	Ca 40.078 strontium 38 Sr 87.62 bartum 56 Baa 137.33 radium 88	57-70 ★ 89-102	Sc 44.956 yttrium 39 Y 88.906 lutetium 71 Luu 174.97 lawrencium 103	Ti 47.867 zirconium 40 Zr 91.224 hafnium 72 Hf 178.49 rutherfordium 104	V 50.942 niobium 41 Nb 92.906 tantalum 73 Ta 180.95 dubnium 105	Cr 51.996 molybdenum 42 Mo 95.94 tungsten 74 W 183.84 seaborgium 106	Mn 54.938 technetium 43 Tcc 198 rhenium 75 Ree 186.21 bohrium 107	Fe 55.845 ruthenlum 44 Ru 101.07 osmium 76 OS 190.23 hassium 108	Co 58.933 rhodium 45 Rh 102.91 iridium 77 Ir 192.22 meitnerdum 109	Ni 58,693 palladium 46 Pd 106,42 platinum 78 Pt 195,08 ununnilium 110	Cu 63.546 silver 47 Agg 107.87 gold 79 Au 196.97 unununium 111	Zn 65.39 cadmium 48 Cd 112.41 mercury 80 Hg 200.59 ununbium 112	Ga 69.723 Indium 49 In 114.82 thallium 81 TI 204.38	Ge 72.61 110 50 Sn 118.71 lead 82 Pb 207.2 ununquadium	As 74.922 antimony 51 Sb 121.76 bismuth 83 Bi 208.98	Se 78.96 tellurium 52 Te 127.60 potonium 84 PO [209]	Br 79.904 iodine 53 I 126.90 astatine 85 At [210]	Kr 83.80 xenon 54 Xe 131.29 radon 86 Rn [222]
K 39.098 rubidium 37 Rbb 85.468 cassium 55 CS 132.91 francium 87	Ca 40.078 strontium 38 Sr 87.62 bartum 56 Baa 137.33 radium 88	57-70 ★ 89-102	Sc 44.956 yttrium 39 Y 88.906 lutetium 71 Luu 174.97 lawrencium 103	Ti 47.867 zirconium 40 Zr 91.224 hafnium 72 Hf 178.49 rutherfordium 104 Dc	V 50.942 niobium 41 Nb 92.906 tantalum 73 Ta 180.95 dubnium 105	Cr 51.996 molybdenum 42 Moo 95.94 tungsten 74 W 183.84 seaborgium 106	Mn 54.938 technetium 43 Tcc 198] rhenium 75 Ree 186.21 bohrium 107	Fe 55.845 ruthenlum 44 Ru 101.07 osmium 76 OS 190.23 hassium 108	Co 58.933 rhodium 45 Rhh 102.91 iridium 77 Ir 192.22 meitnerium 109	Ni 58,693 palladium 46 Pd 106,42 platinum 78 Pt 195,08 ununnilium 110	Cu 63.546 silver 47 Agg 107.87 gold 79 Au 196.97 unununium 111	Zn 65.39 cadmium 48 Cd 112.41 mercury 80 Hg 200.59 ununbium 112	Ga 69.723 Indium 49 In 114.82 thallium 81 TI 204.38	Ge 72.61 tin 50 Sn 118.71 lead 82 Pb 207.2 ununquadium 114	As 74.922 antimony 51 Sb 121.76 bismuth 83 Bi 208.98	Se 78.96 tellurium 52 Te 127.60 potonium 84 PO [209]	Br 79.904 iodine 53 I 126.90 astatine 85 At [210]	Kr 83.80 xenon 54 Xe 131.29 radon 86 Rn [222]
K 39.098 rubidium 37 Rb 85.468 caesium 55 CS 132.91 francium 87 Fr	Ca 40.078 strontlum 38 Sr 87.62 barlum 56 Ba 137.33 radium 88 Ra	57-70 ★ 89-102 ★ ★	Sc 44.956 yttrium 39 Y 88.906 lutetium 71 Luu 174.97 lawrencium 103 Lr	Ti 47.867 zirconium 40 Zr 91.224 hafnium 72 Hf 178.49 rutherfordium 104 Rf	V 50.942 niobium 41 Nb 92.906 tantalum 73 Ta 180.95 dubnium 105 Db	Cr 51.996 molybdenum 42 MO 95.94 tungsten 74 W 183.84 seaborglum 106 Sg	Mn 54.938 technetium 43 Tc 198] rhenium 75 Re 186.21 bohrlum 107 Bh	Fe 55.845 ruthenlum 44 Ru 101.07 osmium 76 OS 190.23 hassium 108 HS	Co 58.933 rhodium 45 Rh 102.91 iridium 77 Ir 192.22 meitnerium 109 Mt	Ni 58.693 palladium 46 Pd 106.42 platinum 78 Pt 195.08 ununnilium 110 Uun	Cu 63.546 silver 47 Ag 107.87 gold 79 Au 196.97 unununium 111 Uuu	Zn 65.39 cadmium 48 Cd 112.41 mercury 80 Hg 200.59 ununblum 112 Uub	Ga 69.723 Indium 49 In 114.82 thailium 81 TI 204.38	Ge 72.61 118.71 118.71 lead 82 Pb 207.2 ununquadium 114 Uuq	As 74.922 antimony 51 Sb 121.76 bismuth 83 Bi 208.98	Se 78.96 tellurium 52 Te 127.60 polonium 84 PO [209]	Br 79.904 iodine 53 I 126.90 astatine 85 At [210]	Kr 83.80 xenon 54 Xe 131.29 radon 86 Rn [222]

*Lanthanide series

**Actinide series

ine	lanthanum 57	cerium 58	praseodymium 59	neodymium 60	promethium 61	samarium 62	europium 63	gadolinium 64	terbium 65	dysprosium 66	holmium 67	erbium 68	thulium 69	ytterbium 70
103	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
	138.91	140.12	140.91	144.24	[145]	150.36	151.96	157.25	158.93	162.50	164.93	167.26	168.93	173.04
	actinium	thorium	protactinium	uranium	neptunium	plutonium	americium	curium	berkelium	californium	einsteinium	fermium	mendelevium	nobelium
S	89	90	91	92	93	94	95	96	97	98	99	100	101	102
	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No
	[227]	232.04	231.04	238.03	[237]	[244]	[243]	[247]	[247]	[251]	[252]	[257]	[258]	[259]

Calculated electron distribution function for bulk GaAs as a function of electron kinetic energy



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Calculated electron distribution function for bulk GaAs as a function of electron kinetic energy



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Calculated electron distribution function for bulk GaAs as a function of electron kinetic energy



Average electron kinetic energy as a function of impact parameter



Average electron kinetic energy as a function of ion charge Z



Calculated average kinetic energy of electrons for bulk GaAs as a function of time



Calculated average kinetic energy of electrons for bulk GaAs as a function of time



Conclusions

- The effect of the potential of the incident ion is reflected in the phonon and impurity assisted electron transitions through modifying ("renormalizing") the scattering of electrons with phonons and impurities via the time dependent potential of the ion projectile
- This method can offer unique ability to study the change in the electron dynamics when a single projectile characteristic is modified.
- The same numerical code as with the excitation with a laser field is used.

Thank you for your attention!