2. Defects and semiconductor technology

2.1 Device effects of defects
2.2 Degradation
2.1 Device effects of defects

„Über Halbleiter sollte man nicht arbeiten, das ist eine Schweinerei, wer weiß ob es überhaupt Halbleiter gibt.“

[Pauli 1931]
The first transistor and IC

Transistor as invented by Bardeen and Brattain at Bell labs, 1947

Integrated circuit of J. Kilby, 1958
“In 1958, the year of the invention of the integrated circuit, a single transistor sold for about $10. Today, it is possible to buy more than 50 million transistors for that price.”

[Kilby: 2000]
In 1965 Gordon E. Moore postulated his law: The doubling of transistors per circuit every couple of years. Intel expects that it will continue at least through the end of this decade.
Moore’s laws

Functional form of key semiconductor industry business trends (Tx – transistors)

The exponential expansion of the total number of transistors per chip or area against the time (in years) over the last half-century is known as (the original) Moore’s law.
The field-effect transistor (FET)

Structure of a MOSFET (metal–oxide–semiconductor FET). The electrical contact to the gate is separated from the semiconductor by a thin layer of insulator, typically silicon dioxide.
Mobility of electrons in n-type semiconductors

Mobility related to acoustic phonon interaction

$$
\mu_v \propto (m^*)^{-5/3} T^{-3/2}
$$

Mobility related to ionized donors

$$
\mu_D \propto (m^*)^{-1/2} N_D T^{3/2}
$$

$$
\frac{1}{\mu_n} = \frac{1}{\mu_v} + \frac{1}{\mu_D}
$$

Conductivity

$$
\sigma = ne\mu_n
$$

Mobility of electrons in Si

[Yu, Cardona 2001]
Scattering at dislocations

Two contributions:
- Scattering due to the deformation potential
- Linear arrangement of charged scattering centers

Type and direction of dislocations are important:
$I–U$ characteristics measured parallel and perpendicular to the dislocations are different

Mobility of electrons in n-type Ge before and after plastic bending. Curve (a) was calculated with the space-charge cylinder model.

[Seeger 1997]
Electron mobility and dislocation density

Effect of the grading rate in the buffer on the density of threading dislocations and the electron mobility measured at 0.4 K. The dotted line is an extrapolation showing that the mobility is not limited by the dislocations once their density is below $10^7$ cm$^{-2}$ (thickness of graded layer > 0.5 µm).

[Ismail 1996]
Reverse bias $I$–$U$ characteristics for InP photodiodes containing different dislocation densities (given in cm$^{-2}$)

[Beam et al. 1992]
Dislocations at the p–n junction

- Dislocations as electrically active defects cause a shortening of the junction
- Transport of minority carriers under reverse bias affected
- Energy levels of dislocations (recombination centers): source of electrical noise
- Dopant precipitation at dislocations: local field enhancement under reverse bias, drop in reverse breakdown voltage
- Microplasma (high electron–hole density) formation
Charged-dislocation model

Model of Read (1957): The line charge of the dislocation is screened by a cylindrical space charge region, i.e. in an n-type semiconductor a negative dislocation is surrounded by positively charged donors.

Radius of the Read cylinder:

\[ R = \sqrt{\frac{Q}{e\pi(N_D - N_A)}} \]

(Q charge per unit length)

Smearing out of the screening cloud for \( T > 0 \)
Influence of dislocations on the p–n junction

Scheme according to Holt (1996) illustrating the absorption of the diffusing impurity (e.g. phosphorus) by dislocations and the retardation of the diffusion front. In this way, cusps in the p–n junction are produced. The magnitude of the effect depends on the depth of the dislocation; shallower ones produce the larger effects. A and B are strongly decorated dislocations. The impurity atmosphere at dislocation C is weaker.
Structure of a FET. Si implantation is used for the production of the n-conductive channel. Lateral isolation is provided by amorphization in B. The symmetrical n⁺ contacts are made of Ni/Au–Ge, the gate by Ti–Pt–Au. The drain/source–gate separation is 2 µm.
Precipitates in FET structures

Laser scattering tomography (LST) of precipitates (a) decorating dislocations in the substrate and (b) in the channel between drain and gate.

[Castagné et al. 1992]
Influence of the precipitates on the breakdown voltage (a) and the threshold voltage (b) of the GaAs FET. The symbols in (b) represent different lengths of the channels.

[Castagné et al. 1992]
2.2 Degradation

- Limitation of the lifetime of semiconductor devices, especially optoelectronic devices
- Defect formation during operation
- Classification of degradation modes, recombination enhanced defect generation and motion
Scheme of a laser diode

Basic structure of a laser diode

Optical resonator realized with the Fabry–Perot condition

\[ m\lambda = 2nL \]

\( m \) integer number, \( \lambda \) wavelength, \( n \) refraction index, \( L \) resonator length

Population inversion at the p–n junction as the lasing condition (\textit{i.e.} stimulated emission larger than optical absorption)
Nichia blue laser diode consisting of a stack of AlGaN, GaN, and InGaN layers. The SiO$_2$ islands are stoppers for threading dislocations.

TEM cross-section image of the layer containing threading dislocations [Lester et al. 1995]
Influence of dislocations on device efficiency

Light output as a function of the dislocation density in the active region for various laser diodes according to Lester et al. (1995) and Sugahara et al. (1998)
Degradation of light-emitting devices

A representative *degradation* curve of light output versus time. The scale along the ordinate can vary over hours to ten on thousands of hours.
Formation of dark-line defects

Micro-electroluminescence distribution of ⟨110⟩-oriented dark-line defects in a high-power GaAs light-emitting diode of the 1980ies.
Dislocations in a GaAs LED

Dislocations in a GaAs light-emitting diode in EBIC (a) and cathodoluminescence (b) images. Note the vanishing contrast in (b) for the dislocations 1 to 3.

[Schreiber et al. 1984]

EBIC – electron beam induced current
Dark-line defects and dislocation motion

Dark-line defects of a GaAlAs laser diode in the electroluminescence distribution and in a transmission electron microscope image. B denotes a threading dislocation and A the formation of a dislocation dipole in a ⟨100⟩ direction. \( g \) is the diffraction vector.

[Hutchinson, Dobson 1980]
Growth of dark-line defects

Scheme of the growth of a dislocation network in the active layer of the laser device. (a) Initially, the dislocation $\mathbf{PN}$ with the Burgers vector $\mathbf{b}$ crosses the layer; (b) climb into the active zone; (c) further climb confined to the active zone causes elongation along the [100] direction.

[Hutchinson, Dobson 1975]
Dislocation climb in the active layer

Two models proposed for the extension of \(\langle 100\rangle\)-oriented dark-line defects in degraded optoelectronic devices via dislocation climb. (a) Model related to absorption of interstitials, (b) emission of vacancies.
Influencing defects by carrier recombination

- Release of energy by recombination of excess carriers (photons, phonons)
- Recombination energy may be directly used for defect reactions (generation, motion, transformation) – recombination enhanced defect reaction
- Energy transfer can be directly an special sites on the dislocation (kinks) – recombination enhanced dislocation glide
- Stimulated activity of the kink migration: increase in the dislocation velocity
Electron-beam-stimulated dislocation motion

Moving dislocations near a scratch on GaAs observed by cathodoluminescence imaging

[Höring et al. 2000]
**Recombination enhanced dislocation glide**

Temperature dependence of the thermal and recombination-enhanced dislocation velocity $v$ of polar $60^\circ \alpha$ and $\beta$ dislocations in GaAs

$[\text{Maeda, Takeuchi 1983}]$

\[ v = v_0 \tau^m \exp \left( -\frac{Q}{k_B T} \right) + \eta I \exp \left( -\frac{Q - \Delta E}{k_B T} \right) \]

($Q$ activation energy in the dark, $I$ beam current density, $\Delta E$ reduction in the activation energy by the electron beam, $\tau$ stress, $m$ stress exponent, $v_0$ and $\eta$ prefactors)
Defect structures

♦ 〈110〉-oriented dark-line defects  (GaAlAs)

dislocation glide enhanced by nonradiative recombination of carriers

♦ 〈100〉-oriented dark-line defects  (GaAlAs)

recombination-enhanced dislocation climb

♦ Dark-spot defects  (InGaAsP)

reaction between metal contacts and the matrix, microdefects
Degradation modes

♦ **Catastrophic optical damage** (< 1 h)

Local heating at the mirror surface related to high output-power density

♦ **Rapid degradation** (< 100 h)

Formation of dark-line defects

♦ **Gradual degradation** (several 1000 h)

Microdefects (loops, point defect clusters)

♦ **Facet degradation** (> 10000 h)

Oxidation or point defect formation at the mirror facets
References