Opto-Electronics Review 25 (2017) 148–170

Contents lists available at ScienceDirect

Opto-Electronics Review

journal homepage: http://www.journals.elsevier.com/opto-electronics review

Review

Ion etching of HgCdTe: Properties, patterns and use as a method for defect studies[☆]

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ARTICLE INFO

Article history:
Received 16 January 2017
Accepted 28 March 2017
Available online 29 April 2017

This review is dedicated to the memory of our friend and colleague Prof. V.V. Bogoboyashchyy.

Keywords:
HgCdTe
Ion etching
Photodetectors
Defects
Doping

ABSTRACT

Analysis is performed of the contemporary views on the effect of ion etching (ion-beam milling and reactive ion etching) on physical properties of HgCdTe and on the mechanisms of the processes responsible for modification of these properties under the etching. Possibilities are discussed that ion etching opens for defect studies in HgCdTe, including detecting electrically neutral tellurium nanocomplexes, determining background donor concentration in the material of various origins, and understanding the mechanism of arsenic incorporation in molecular-beam epitaxy-grown films.

1. Introduction

$Hg_{1-x}Cd_xTe$ (MCT) solid solutions, since they were synthesized for the first time at Royal Radar Establishment (UK) and Lviv State Pedagogical Institute (USSR) in the middle of the last century [1,2], have remained the basic material for the fabrication of highly effective photodetectors operating in the infrared (IR) part of the spectrum (2.5–20 μm) [3]. This status of MCT is pre-defined by the electronic structure of this material and is expected to remain such for at least two decades more.

In MCT technology, methods of 'dry etching', including ion-beam milling or reactive ion etching, are used quite widely. These processing techniques are based on the irradiation of the surface of the material with low-energy (0.2–2 keV) ions of noble gases (mostly Ar) or mixture of Ar with chemically active gases (H_2, CH_4). Initially, such etching was used for dry cleaning and sputtering of the material with the aim of formation of specific surface topology and/or contact areas of sensitive elements of photodetectors [4–6]. Later, ion etching was used to form the topology of MCT-based matrix-type mesa-diodes, including multi-color ones [7–9]. The results of the use of various types of dry etching in application to MCT *etching* in a sense of sputtering (material removal) were reviewed in Ref. [10], yet the effect of such treatment on *physical* properties of MCT in that paper was not considered.

In 1981, in a patent by Wotherspoon [11] it was declared, for the first time, that ion etching of vacancy-doped *p*-MCT (where conductivity type was defined by intrinsic acceptors, mercury vacancies V_{Hg}) led to *p*-to-*n* conductivity type conversion (CTC). This effect was proposed as a tool for fabrication of *p*-*n* junctions of photodiodes. Wide-scale studies of the effect of ion etching on the properties of MCT began after 1990, and at that time, this method also was introduced into industrial production of photodiodes. As the properties of MCT change in a similar way under both ion

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[☆] This article is an expanded version of the scientific reports presented at the International Conference on Semiconductor Nanostructures for Optoelectronics and Biosensors 2016 ICSeNOB2016, May 22–25, 2016, Rzeszow, Poland.

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http://dx.doi.org/10.1016/j.opelre.2017.03.007
1896-3757/

List of abbreviations and symbols used throughout the text

Abbreviations

AO	anodic oxide
CTC	conductivity type conversion
DC	direct current
EBIC	electron beam induced current
IE	ion etching
ISOVPE	isothermal vapor-phase epitaxy
LBIC	laser-beam induced current
LPE	liquid phase epitaxy
MBE	molecular beam epitaxy
MCT	mercury cadmium telluride, $Hg_{1-x}Cd_xTe$
MOCVD	metal-organic chemical vapor deposition
MSA	mobility spectrum analysis
RF	radio frequency
SIMS	secondary-ion mass-spectroscopy
VPE	vapor-phase epitaxy
WBPL	wide-bandgap protective layer

Symbols

a	HgCdTe lattice parameter
B	magnetic field
C_{V0}	initial concentration of mercury vacancies in the damaged area
C_{W0}	initial concentration of mercury bivacancies in the damaged area
d_j	conductivity type conversion depth
d_r	conductivity type conversion depth reduced to mercury vacancy concentration
D	ion dose
D_I	mercury interstitial diffusion coefficient
D_V	mercury vacancy diffusion coefficient
E_C	energy of the conduction band
E_F	Fermi energy
E_g	energy gap
E_M	energy of mercury interstitial migration
E_V	energy of the valence band
E	ion energy
e	elementary charge
$\mathbf{J}$ ($\mathbf{J}_{\mathrm{Hg}}$)	mercury flux
j	ion current density
Hg_I	interstitial mercury
$[\mathrm{Hg}_I]_S$	concentration of Hg_I in the diffusion source under ion etching
k_B	the Boltzmann constant
K_F	equilibrium constant for the reaction between mercury vacancy and interstitial
k_F	reaction rate constant between mercury vacancy and interstitial
k_w	reaction rate constant between mercury bivacancy and interstitial
K_{rM}	equilibrium constant for the reaction between interstitial mercury and I-group acceptor
K_X	equilibrium constant for the reaction between interstitial mercury and arsenic atom
L_d	defect layer thickness, radius of defect zone
L_y	protective layer thickness
l_0	a factor
N_0	node density in crystal (sub)lattice
N_A	acceptor concentration
N_{As}	arsenic concentration
N_{BD}	background donor concentration
N_D	donor concentration
N_A-N_D (N_D-N_A)	concentration of uncompensated acceptors (donors)
N_{In}	indium concentration
N_{tr}	density of capture centers for mercury interstitials
n	electron concentration
n_{77i}	electron concentration measured straight after ion etching
n_{77f}	electron concentration measured after relaxation
$n_{77(0)}$	electron concentration measured before ion etching
n_i	intrinsic carrier concentration
p_{77}	hole concentration measured at 77 K
$R(\mathbf{r},t)$	rate of mercury interstitial capture on radiation-induced defects
R_H	the Hall coefficient
R_p	projected ion path
r_F	mercury interstitial caption radius on a mercury vacancy
r_w	mercury interstitial caption radius on a mercury bivacancy
r_0	screening length (radius)
S	effective cross-section of the defect formation zone
S_I	a function describing Hg_I source
T	temperature
T_{cr}	temperature of the cracker cell in MBE of MCT
T_{src}	temperature of the arsenic source in MBE of As-doped material
T_s	sample temperature during ion etching
T_{sb}	substrate temperature during MCT growth
t	time
V_{Hg}	mercury vacancy
$W_{\mathrm{Hg}}^{\times}$	neutral mercury bivacancy
x	alloy composition (CdTe molar fraction in $Hg_{1-x}Cd_xTe$)
x_a	alloy composition in the active layer of heteroepitaxial HgCdTe structure
x_j d_j	conversion depth
x_y, y	composition at the surface of graded-gap wide-bandgap protective layer
z	co-ordinate axis normal to crystal surface
δ_0	mercury deficiency
ε	dielectric constant
ΔH_{cX}	enthalpy of the formation of the complex of interstitial mercury with arsenic
ΔL_0	thickness of the defect layer that acts as a mercury source
μ_{n77}, μ_{p77}	carrier mobility measured at 77 K
σ	conductivity
φ	electric potential
Φ	ion fluence
τ	non-equilibrium carrier lifetime

milling and reactive ion etching, we shall further refer to both kinds of treatment as to 'ion etching' (IE). Also, as the main patterns of the changes in the properties of MCT under IE are valid for the material with *p*- and *n*-type, we shall often speak of 'modification' of these properties.

Some aspects of the effect of IE on the properties of MCT were reviewed by Ivanov-Omskii and Mynbaev in 2002 [12]. At that point, it looked like that the development of the technology was far ahead of understanding of physical processes that occurred under IE. In the last 15 years this understanding has demonstrated a substantial progress. In particular, the effect of IE on the properties of